5-2013

Transient Effects on Dynamic Torque for Butterfly Valves

Trevor N. Price

TRANSIENT EFFECTS ON DYNAMIC TORQUE

FOR BUTTERFLY VALVES

by

Trevor N. Price

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Michael C. Johnson Major Professor	Blake P. Tullis Committee Member

Kevin P. Heaslip
Committee Member

UTAH STATE UNIVERSITY
Logan, Utah

2013

ABSTRACT

Transient Effects on Dynamic Torque for Butterfly Valves

by

Trevor N. Price, Master of Science

Utah State University, 2013

Major Professor: Dr. Michael C. Johnson

Department: Civil and Environmental Engineering

Butterfly valves are versatile components widely used in hydraulic systems as shutoff and throttling valves. Butterfly valve components must be able to withstand the forces and torques that are generated with use. Dynamic torque data are usually obtained in a test lab for a variety of steady state flow conditions; however the dynamic torque under transient (unsteady flow) conditions may be significantly different than that found in the laboratory. If a valve is closed too fast, especially in long systems, large transient pressures are generated and travel as waves through the pipeline. These transient waves increase the pressure difference across the valve, which in turn increases the dynamic torque that is applied to the valve. The effects of the increased dynamic torque are more significant in larger butterfly valves since dynamic torque is a function of the diameter raised to the third power. If the increased dynamic torque is larger than the torque that the valve was built to withstand, valve or actuator failure could result. The objective of this research was to examine the effect of transients on dynamic torque in a 48-inch diameter butterfly valve operation as a function of pipe length and valve closure time (starting at full open) and compare the results to traditional steady state dynamic torque data. It was found that longer pipeline lengths along with smaller valve closure times created the largest percent difference in transient dynamic torque from the steady state dynamic torque. This difference was as high as 711% in a 20,000-foot long pipeline when the valve was closed in 36 seconds. Transient effects should be considered in the design and manufacturing of butterfly valves as well as during the operation of the valve once it is installed.

(93 pages)

ACKNOWLEDGMENTS

I would like to give thanks to those who helped and contributed with this project. First of all, many thanks go to my wife, Jessica, for her support while I worked on this graduate research and throughout my college career. I would especially like to thank Dr. Michael Johnson, my major professor, for giving me the opportunity to research this topic and for all of his advice and guidance. I would also like to thank my committee members, Dr. Blake Tullis and Dr. Kevin Heaslip, for their assistance in completing this project. The Utah Water Research Laboratory provided me with a workspace to grind away at my work which is appreciated. Their financial support is also greatly appreciated. I would like to extend gratitude to all of my family and friends for their support and to my fellow graduate students for their advice and consultation.

Trevor N. Price

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATIONS

C_Q	=	Discharge Coefficient
C_t	=	Dynamic Torque Coefficient
$C_{t\theta}$	=	Dynamic Torque Coefficient at a given valve opening θ
C_v	=	Valve Coefficient
D	=	Valve Diameter
D_d	=	Valve Disc Diameter
ft	=	Feet
g	=	Gravitational Acceleration (32.2 ft/s^2)
ΔH	=	Head Loss
K	=	Loss Coefficient
ΔP	=	Differential Pressure
ΔP_θ	=	Differential Pressure at a given valve opening θ
$P_{downstream}$	=	Pressure Downstream of the valve
$P_{upstream}$	=	Pressure Upstream of the valve
psi	=	Pounds per Square Inch
Q	=	Flow Rate
s	=	Seconds
sg	=	Specific Gravity
T_d	=	Dynamic Torque
$T_{d\theta}$	=	Dynamic Torque at a given valve opening θ
$T_{d,steady\ state}$	=	Steady State Dynamic Torque

$T_{d,transient}$	=	Transient Dynamic Torque
V	=	Average Velocity
WHAMO	=	Water Hammer and Mass Oscillation
%	=	Percent
θ	=	Valve Opening (Closed = 0)

CHAPTER

I. INTRODUCTION

Butterfly valves are versatile components widely used in hydraulic systems as shutoff and throttling valves. Butterfly valve components must be able to withstand the forces and torques that are generated with use (American Water Works Association 2012). It is also necessary to know the maximum torque required for valve operation in order to design/select the proper lever or actuator that will be used to open and close the valve under every operating condition as well as properly size the shaft or stem of the valve. Dynamic torque data are usually obtained in a test lab with the system operating at a steady state condition; however the dynamic torque under transient (unsteady flow) conditions may vary significantly from the steady state laboratory conditions. The objective of this research was to examine the effect of transients on dynamic torque in butterfly valve operation by changing the length of the pipeline in the system where the butterfly valve is being used and also by changing the time in which the valve will be closed from the full open position. The transient and steady state dynamic torque data will be compared.

If a valve is closed too quickly, especially in long systems, large transient pressures are generated and travel as waves through the pipeline. These transient waves increase the pressure difference across the valve, which in turn increases the valve's dynamic torque. The effects of the increased dynamic torque are more significant in larger butterfly valves since dynamic torque is a function of the diameter to the third power. If this increased dynamic torque is larger than the torque that the valve was built to withstand, then failure of the valve could result. Depending on the system, valve failure could cause significant financial losses to those that are dependent on the system and could potentially cause harm or death to others.

Although transient events may not increase the dynamic torque applied to the butterfly valve enough to cause problems to the valve, it is increasing the dynamic torque and therefore should be considered in the design, manufacture, and use of the valve. It is probable that other components in the pipeline system are weaker than the butterfly valve and will fail before the valve. However, if there is a chance that transient events increase the dynamic torque enough to cause failure of the valve, it is important to investigate this topic further. Due to the fact that very long pipeline systems (up to 20,000 feet) were analyzed, it would have been very difficult to perform a physical model of this project because of the lack of facilities to test the system. Therefore, this research is theoretical and was completed using software that is described in the following paragraph.

Water Hammer and Mass Oscillation (WHAMO) software, created by the Army Corp of Engineers, was used to analyze the steady and unsteady flow systems for this research (U.S. Army Corps of Engineers Construction Engineering Research Laboratory 2010). This research examined the dynamic torque characteristics of a 48-inch butterfly valve. Valve data and valve dynamic torque coefficients under steady-state conditions for this valve were previously obtained through laboratory testing at the Utah Water Research Laboratory in Logan, UT. Further details of the research procedure are outlined in later sections.

II. LITERATURE REVIEW

Literature regarding the transient effects on dynamic torque for butterfly valves was not found. No documented cases of butterfly valve failures due to transients and/or dynamic torque were found in the literature search. However, failure could still be occurring and no evidence be posted publicly. It is highly likely that any valve failures would not be publicly documented as such press may harm the valve manufacturer. Listed in the subsequent paragraphs are information for two failed systems where it is believed that transient pressures, created by closing a butterfly valve, were the cause of the failure. Literature containing basic information about butterfly valves, dynamic torque, and transients was the main source for information in this research and is listed later in this section.

Flow Science (2008) lists a project on their website that they worked on for the Puerto Rico Aqueduct and Sewer Authority. This project consisted of performing a hydraulic transient analysis of the failure of the Puerto Rico Superaqueduct treated water transmission pipeline. The system being analyzed stretched over approximately 30 miles and consisted of 72-inch pre-stressed concrete cylinder pipe with a series of 60-inch diameter butterfly valves on the downstream end. The analysis was to investigate the transient events that occurred when the butterfly valves were being closed. No further information was found regarding the results of the study.

Tullis Engineering Consultants (2012) provided an expert witness investigation on the failure of a 6-inch riser pipe in a sprinkler system in an office building. They provided forensic engineering services to determine if transient pressures that were generated by closing a butterfly valve were the cause of the failure. The case has not been decided. Although these two examples do not show the failure of the butterfly valve itself, failure is occurring in the pipeline and the closing of the butterfly valve was involved.

The American Water Works Association's (AWWA) (2012) M49 manual, Butterfly Valves: Torque, Head Loss, and Cavitation Analysis was used for most of the background information about butterfly valves for this research. Information about dynamic torque and the standard procedure for calculating this torque was found in this manual. The background section in Chapter III of this report describes this information in more detail. Hydraulics of Pipelines: Pumps, Valves, Cavitation, Transients by J. Paul Tullis (1989) was used to further understand transients. Detail about transients is also discussed in Chapter III of this report.

III. TRANSIENT EFFECTS ON DYNAMIC TORQUE

Background

Butterfly valves are commonly used in hydraulic systems. These valves consist of a circular disc, which is supported by a shaft connected to an actuator for opening and closing the valve. The circular disc can have many different designs as long as it can seal properly when closed and that the valve can withstand the torque applied due to operation. The shaft configuration [typically passing through the center of the disc or offset to either side (upstream or downstream) of the disc], the disc design, and the actuator design (e.g., hand levers; manual gear actuators; or electrical, hydraulic, or pneumatic power actuators) can influence the dynamic torque characteristics of the valve.

In order to design a butterfly valve for torque, head loss, and cavitation, testing of the valve is required. This testing is most commonly performed when the system is operating at steady state. Testing can be done by physically testing the valve in a laboratory, adjusting data from tests of a different sized but similar valve, or running a Computational Fluid Dynamics simulation of the valve.

Torque, for butterfly valves, is the turning force needed to rotate the valve disc or hold it in position (American Water Works Association 2012). When designing a valve to withstand the torque that will be applied during operation, there are ten separate torque components to consider. These components are (1) seating (and/or unseating) friction torque, (2) packing friction torque, (3) hub seal friction torque, (4) bearing friction torque, (5) thrust bearing friction torque, (6) weight and center of gravity torque, (7) buoyancy torque, (8) lateral offset or eccentricity torque, (9) dynamic or fluid dynamic torque, and (10) hydrostatic unbalance torque (American Water Works Association 2012). The buoyancy torque (7) and the thrust bearing torque (5) are considered negligible in butterfly valves (American Water Works Association 2012). Components one through five are considered passive or friction based and usually control the torque for smaller valve sizes -12 inches and smaller (American Water Works Association 2012). While components six through ten are considered active or dynamically generated and control the torque for larger valves -30 inches and larger (American Water Works Association 2012). Dynamic torque (9), T_d, is a flow-induced torque determined as a function of valve geometry, flow rate, and valve position (American Water Works Association). Dynamic torque is a function of the diameter to the third power; therefore it becomes increasingly more significant as valve diameters increase (Equation 1).

$$T_d = C_t * D_d^3 * \Delta\mathrm{P} \tag{1}$$

In Equation 1, C_t is the dynamic torque coefficient, D_d is the butterfly valve disc diameter, and ΔP is the differential pressure across the valve (American Water Works Association 2012). Figure 1 is a simple sketch to show where the dynamic torque is applied to the butterfly valve during valve closure.

Hydraulic transients, in the most general term, refer to any unsteady flow in open channel or closed conduits (Tullis 1989). Transients usually occur when there is a sudden change in velocity. Typical causes of transients include filling and flushing pipes, opening or closing valves, starting or stopping pumps, and air moving through the pipe or being released incorrectly (Tullis 1989). An instant or rapid closure of a valve creates a

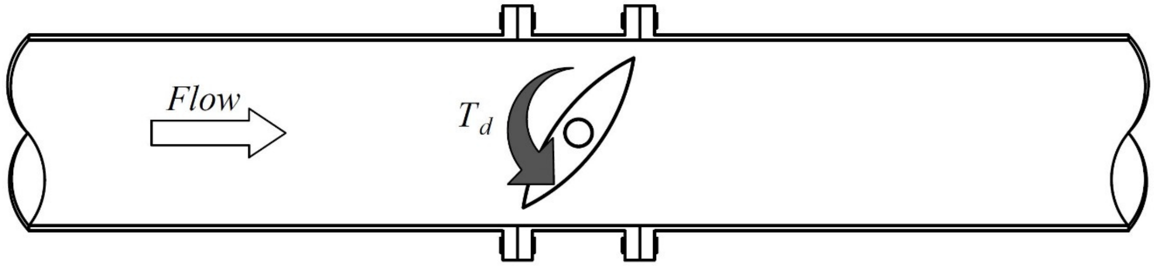

Figure 1: Dynamic Torque Applied to a Butterfly Valve during Valve Closure

sudden change in the velocity and an unsteady flow event. This sudden change in velocity causes an increase of pressure in the conduit (Tullis 1989). This increase of pressure potentially was not accounted for in the structural design of the system components. Transients are responsible for many pipe and equipment failures (Tullis 1989). Since most design specifications are tested and evaluated at steady state, transients or unsteady flow conditions may be overlooked when designing elements within the hydraulic system. The purpose of this research is to examine the effect that transients or the increase of pressure surrounding a butterfly valve has on the dynamic torque that is applied to the valve.

Water Hammer and Mass Oscillation (WHAMO) is a computer program, created by the U.S. Army Corps of Engineers, designed to provide dynamic simulations of hydropower, pumping, water distribution and fuel distribution systems (U.S. Army Corps of Engineers Construction Engineering Research Laboratory 2010). The program was created to calculate time variant (transient) flow and head in networks comprised of pipes, valves, pumps, turbines, pump-turbines, and surge tanks. WHAMO was used to provide the data necessary to investigate the transient activity that occurs in the hydraulic system near the butterfly valve.

Experimental Procedure

Software

Water Hammer and Mass Oscillation (WHAMO) is a command prompt type software package. The system input data is provided to the program via a user provided text input file. Once this text file has been created, it can be read into the WHAMO program's command prompt window (example: 48A5000A-T90.TXT). The program then prompts the user to specify file names for saving the output file, plot data file, and spreadsheet output file if these files were called for in the text file. An example text file that was created to analyze a 48-inch butterfly valve in a 5,000 foot long pipeline with a 90-second valve closure time is displayed in Appendix A.

System Details

All of the system details and commands to operate the system in the WHAMO program were outlined in the text file including the components of the system. Figure 2 shows the basic outline of the pipeline system that was evaluated. Each node had an elevation of zero and was linked by either a conduit or a valve. The first and last nodes

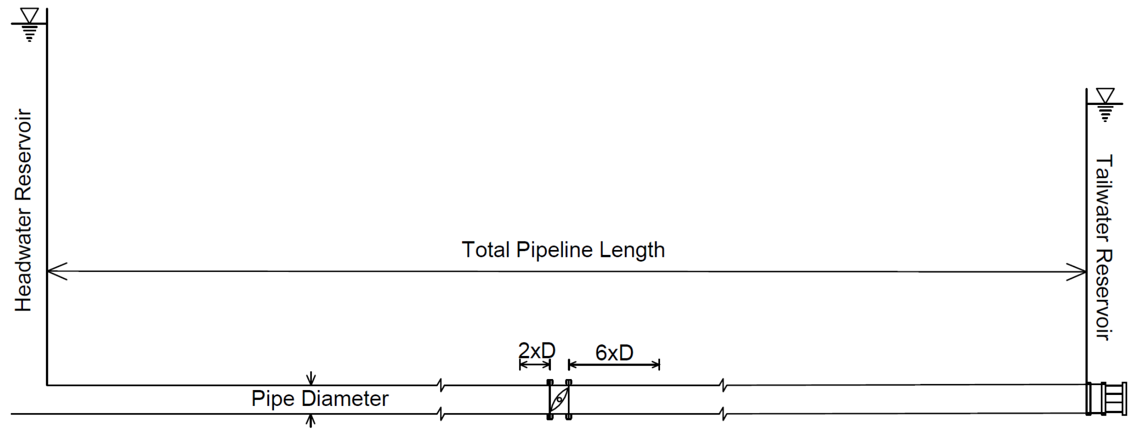

Figure 2: Outline of the Pipeline System

of the system evaluated in this study were reservoirs. The headwater reservoir had a constant surface water elevation of 132 feet for most of the test scenarios while the tail water reservoir had a water surface of 100 feet. In the 20,000-foot long pipeline scenario for both the steady state and transient analysis, the headwater reservoir water surface elevation was bumped to 382 feet and the downstream reservoir water surface was bumped to 350 feet. The headwater reservoir water surface elevation in the 10,000-foot long pipeline was bumped to 232 feet with the tail water elevation at 200 feet. This was done to keep the downstream pressure values from approaching vapor pressure in the transient analysis and causing column separation to occur. It is no longer possible to predict system activity if the pressure drops below vapor pressure and creates large vapor cavities. The 48-inch diameter steel pipes had a wall thickness of 0.375 inches, modulus of elasticity of 30,000,000 psi, and Darcy-Weisbach friction factor of 0.015. After the first reservoir location, a pipeline connected the reservoir to the upstream end of a butterfly valve. The length of this pipeline section was specified with each test. Discharge coefficients specified at each 5-degree valve opening was supplied for the butterfly valve. The valve discharge coefficient data that was needed as input into the WHAMO software was obtained by converting flow coefficient data that came from hydraulic testing conducted previously at the Utah Water Research Laboratory under steady state conditions. The procedure for converting this data is evaluated in the next section.

Following the butterfly valve, the pipeline continued downstream connecting the downstream end of the butterfly valve to a 48-inch Howell-Bunger valve, which acted as a downstream flow control entering the downstream reservoir. The length of this section of the pipeline was specified for each test. The butterfly valve was set at 5-degree valve opening increments to acquire data for the steady state conditions. For the transient analysis, the valve was fully open at time equal to zero and closed at a constant rate over the time specified for each test. The Howell-Bunger valve remained at a constant fifty percent valve opening during both the steady state and transient tests. Upstream and downstream pressures were measured in pounds-per-square-inch (psi) at two diameters and six diameters from the valve respectively.

The final data required by the input file were the output file commands as well as the output intervals. The output files included an output file in text format that lists the inputs into the program as well as all of the results from running the program. A plot file was also created to display data in a graphical format in WHAMGR. The last output file recorded data into a spreadsheet format that could be imported into a spreadsheet document such as Microsoft Excel. For this research the spreadsheet output file was primarily used to analyze the results from each test in Microsoft Excel. The computational interval was set to 0.1 seconds for all tests but the output interval was set according to how fast the valve was being closed and was changed for each test at each specified closure time.

Discharge and Dynamic Torque Coefficients

WHAMO uses a default set of discharge coefficients for a standard butterfly valve if nothing is specified in the system details within the text file. However, in this research, discharge coefficient data found in the laboratory testing and specific to this prototype 48-inch butterfly valve were used. By doing so, this coefficient data was used to duplicate the laboratory system in WHAMO in order to compare results of the valve at steady state that were obtained using the WHAMO software with the values from the laboratory tests. The purpose of this served mostly as a check to make sure that the steady state results from WHAMO closely matched the results obtained in the laboratory testing of the valve. After which, transients were introduced to the system using the WHAMO software and steady state dynamic torques were compared to the transient dynamic torques by varying the pipeline length and closure times.

The flow coefficient, C_v, and loss coefficient, K, for the 48-inch butterfly valve were determined using Equation 2 and Equation 3 respectively from experimental data.

$$C_v = Q\sqrt{\frac{sg}{\Delta P}} \tag{2}$$

$$K = \frac{2 * g * \Delta H}{V^2} \tag{3}$$

Where Q is the flow passing through the valve in gallons per minute, sg is the specific gravity of the fluid (1.0007), ΔP is the pressure drop in psi across the valve measured between pressure taps that were located two diameters upstream from the valve and six diameters downstream from the valve, g is the acceleration of gravity (32.2 ft/s^2), ΔH is the head loss across the valve in feet, and V is the average velocity in the pipe in feet per second.

Three values for the flow and loss coefficients were recorded for the valve at each 5-degree valve opening. The average value was used as the representative flow and loss coefficients at each valve opening. However, WHAMO calls for a discharge coefficient, C_Q, as can be seen in Equation 4.

$$Q = C_Q * D^2 * \sqrt{g} * \sqrt{\Delta H} \tag{4}$$

In Equation 4, Q is the flow through the valve in cubic feet per second, D is the valve diameter in feet, g is the acceleration of gravity (32.2 ft/s^2), and ΔH is the head loss across the valve in feet.

Values of K, V, and Q were documented for each run. Using these values, ΔH can be solved for in Equation 3 and then used in Equation 4 along with the pipe inside diameter (3.9375 ft) to solve for C_Q. Using this method, the values of the loss coefficient, K, in the laboratory testing of the butterfly valve were converted to a discharge coefficient, C_Q. The average C_Q value was determined using the average flow and loss coefficient values; this was used in the system details input in the WHAMO program. . These values can be found in Table 1 and in Appendix B.

In order to check the calculated discharge coefficients, the system that was used in the laboratory to test the butterfly valve was recreated in WHAMO to check the results. The upstream conditions of this system had a constant head equivalent to a reservoir of 32 feet. The pipe was 48 inches in diameter and was made of steel with a thickness of 0.375 inches. The total pipeline length was about 800 feet with the butterfly valve located at about the midpoint. Pressure taps were located two diameters upstream from the butterfly valve and six diameters downstream from the valve. Flow was controlled at the downstream end of the pipeline using a free-discharging Howell-Bunger valve.

Simulations for the steady state at several valve openings were completed in WHAMO to check the pressure across the valve with the pressure recorded in the laboratory tests. The Howell-Bunger valve at the end of the system was adjusted to match the flow rate that occurred during the laboratory test for the given valve opening. Once the flow rate was matched, the differential pressure across the valve was compared with the recorded differential pressure from the laboratory test. After checking several valve openings, the differential pressure across the valve from the WHAMO results consistently matched the results recorded from the laboratory tests. Therefore, the discharge coefficient that was converted from the laboratory test's head loss coefficient using Equations 3 & 4 were used in all of the WHAMO simulations for this study.

The dynamic torque coefficients that were calculated from the valve laboratory tests were also applied to this research for calculating the steady state and transient dynamic torques. A list of the torque coefficients for each 5-degree valve opening with zero degrees being closed can be found in Table 1 and in Appendix B. Equation 5 was used in the laboratory testing of the valve to calculate the torque coefficient, $C_{t\theta}$ at each five degree valve opening.

$$C_{t\theta} = \frac{T_d}{D_d^3 * \Delta P} \tag{5}$$

The dynamic torque, T_d, in inch-pounds and the differential pressure, ΔP, in psi were measured in the laboratory testing of the valve. Using these measurements and the diameter of the butterfly valve disc, D_d, in inches the torque coefficient, $C_{t\theta}$, was calculated.

Table 1: Discharge and Torque Coefficients

Valve Opening (degrees)	C_Q	$C_{t\theta}$
5	0.016	0.002
10	0.033	0.005
15	0.055	0.010
20	0.084	0.015
25	0.122	0.021
30	0.160	0.029
35	0.215	0.042
40	0.284	0.059
45	0.366	0.078
50	0.473	0.106
55	0.591	0.140
60	0.738	0.192
65	0.854	0.209
70	0.973	0.228
75	1.089	0.243
80	1.214	0.267
85	1.411	0.302
90	1.587	0.232

Variable Configuration Details

The same system configuration that was described previously in the System Details section and that was put into WHAMO to check the laboratory coefficient data was used to complete this research project. However, there are a few variables that changed with each test. These included the total length of the pipeline and the butterfly valve disc position. The butterfly valve was placed close to the center of the total pipeline length with nodes to record the pressure at two times the diameter (8 feet) upstream of the butterfly valve and six times the diameter (24 feet) downstream of the valve. The remaining distance of the total pipeline length was divided in half with one half being placed between the upstream reservoir and the upstream pressure recording node while the other half was placed downstream of the butterfly valve connecting the downstream pressure recording node to the Howell-Bunger valve at the end of the pipeline. The total length of the pipeline was varied for each set of data. The shortest pipeline length for these tests was 250 feet while the longest was 20,000 feet and included lengths of 500 feet, 1,000 feet, 5,000 feet, and 10,000 feet (Table 2).

Table 2: Total Pipeline Lengths

Total Pipeline Lengths (ft)
250
500
1,000
5,000
10,000
20,000

With regard to the butterfly valve disk position, the valve remained at a constant opening (every five degrees) for the steady state analysis for each pipeline length. For the transient analysis, the valve was closed at different rates for each pipeline length. The valve closure times varied from 36 seconds to 360 seconds and also included times of 54 seconds, 72 seconds, 90 second, 180 seconds, and 270 seconds (Table 3). The selection of the valve closure time intervals was based on the interval being a factor of 18 seconds in order to easily record the upstream and downstream pressures from the WHAMO results at every 5-degree valve opening. For example, if the closure time is 90 seconds, the valve went from fully open (90 degrees) to fully closed in 90 seconds so the pressures at 5-degree valve openings could be recorded every five seconds.

Steady State and Transient Analysis using WHAMO

For each of the total pipeline lengths listed in Table 2, steady state discharge and pressure data were calculated using WHAMO for each 5-degree valve opening. The pressure difference across the valve for each valve opening was then used to calculate the steady state dynamic torque for that valve opening. This procedure is described in the

Table 3: Butterfly Valve Closure Rates

Butterfly Valve Closure Times (seconds)
36
54
72
90
180
270
360

following section. The discharge was recorded in order to calculate the velocity. For this research, it was desired to keep the velocity below 20 feet-per-second in each of the simulations. This procedure was repeated for all valve openings.

The transient analysis for the given pipeline length was performed by setting the WHAMO program to start with the butterfly valve fully open and then to close the valve in the specified timeframe. The program ran the simulation under these conditions and the upstream and downstream pressures were recorded on each side of the valve at the same location as in the steady state analysis. Pressure values were recorded at every 5-degree valve opening in order to calculate the corresponding transient dynamic torque values to compare with the steady state values. This procedure was repeated for each valve closure time listed in Table 3. Once the steady state and transient analysis was completed in WHAMO for the given pipeline length, the process was then repeated for each of the different pipeline lengths.

Dynamic Torque Data

Pressure values two diameters upstream and six diameters downstream of the butterfly valve were recorded at every 5-degree valve opening for both the steady state and transient cases. The pressure difference across the valve was then calculated by subtracting the downstream pressure from the upstream pressure (Equation 6).

$$\Delta P_\theta = P_{upstream} - P_{downstream} \tag{6}$$

In Equation 6, ΔP_θ is the pressure difference across the butterfly valve, $P_{upstream}$ is the pressure upstream of the valve and $P_{downstream}$ is the pressure downstream of the valve.

By rearranging Equation 5, the dynamic torque, $T_{d\theta}$, in inch-pounds, applied to the butterfly valve was calculated for each 5-degree valve opening (Equation 7).

$$T_{d\theta} = C_{t\theta} * D_d^3 * \Delta P_\theta \tag{7}$$

This equation used the dynamic torque coefficient, $C_{t\theta}$, for each five degree valve opening which was previously mentioned and listed in Appendix B, the diameter of the butterfly valve disc, D_d, in inches and the differential pressure across the valve, ΔP_θ, in psi (American Water Works Association 2012).

After calculating the dynamic torque for both the steady state and transient conditions for each pipeline length and each 5-degree valve opening, the transient dynamic torque was compared to the steady state dynamic torque. A percent difference was calculated with the original data being the steady state dynamic torque as shown in Equation 8.

$$Difference\ (\%) = \frac{(T_{d,transient} - T_{d,steady\ state})}{T_{d,steady\ state}} * 100 \tag{8}$$

In this equation, $T_{d,transient}$ is the transient dynamic torque and $T_{d,steady\ state}$ is the steady state dynamic torque.

Experimental Results

The upstream and downstream pressures as well as the discharge data collected from the WHAMO simulations were recorded in a spreadsheet in order to further analyze the results. As mentioned in the previous section, the pressure difference across the valve was calculated using Equation 6 after which the torque was calculated using Equation 7.

The velocity was also calculated from the discharge recorded at each valve opening. Table 4 shows the calculations for the steady state results for the 20,000-foot long pipeline. In Table 4, the 90 degree valve opening corresponds to the valve being fully open and zero degrees when the valve is closed. The steady state dynamic torque in Table 4 was used to compare to the transient dynamic torque for every valve closure scenario for the 20,000 foot pipeline.

The transient results for the 20,000-foot pipeline when closing the valve over a 90 second time interval is shown in Table 5. As can be noted when comparing Tables 4 & 5, the transient pressure differences were larger than the steady state pressure differences, as

Table 4: Steady State Analysis - 20,000 ft Pipeline

Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Q (cfs)	V (ft/s)
5	165.5	151.8	13.7	0.002	3141	8.1	0.6
10	165.1	152.2	12.9	0.005	7500	16.4	1.3
15	164.5	152.9	11.6	0.010	12400	25.8	2.1
20	163.5	154	9.5	0.015	15449	35.7	2.8
25	162.3	155.3	7.0	0.021	16067	44.6	3.5
30	161.4	156.2	5.2	0.029	16657	50.2	4.0
35	160.6	157.2	3.4	0.042	15899	55.0	4.4
40	160	157.8	2.2	0.059	14289	58.1	4.6
45	159.6	158.2	1.4	0.078	12009	60.1	4.8
50	159.4	158.5	0.9	0.106	10516	61.3	4.9
55	159.2	158.6	0.6	0.140	9278	62.1	4.9
60	159.2	158.8	0.4	0.192	8479	62.5	5.0
65	159.1	158.8	0.3	0.209	6934	62.8	5.0
70	159.1	158.8	0.3	0.228	7566	62.9	5.0
75	159.1	158.9	0.2	0.243	5373	63.0	5.0
80	159	158.9	0.1	0.267	2952	63.1	5.0
85	159	158.9	0.1	0.302	3338	63.2	5.0
90	159	158.9	0.1	0.232	2562	63.2	5.0

would be expected. As a result of the larger pressure difference, the transient dynamic torque was larger than the steady state dynamic torque. From Equation 7, the dynamic torque increased proportionally with the increased transient pressure difference since the torque coefficient for each valve opening and valve diameter remained constant. The discharge across the valve was also recorded in Tables 4 & 5 for each specified valve opening, which was used to calculate the velocity. This was a check to ensure that the velocity stays below the limit that was specified previously.

Table 5: Transient Analysis – 90 second closure time - 20,000 ft Pipeline

Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	Transient Torque (in-lbs)	Q (cfs)	V (ft/s)
5	235.8	168.1	67.7	0.002	15521	1.4	0.1
10	250.0	153.9	96	0.005	55815	16.3	1.3
15	244.6	159.5	85.1	0.010	90971	34.3	2.7
20	227.5	176.9	50.5	0.015	82121	48.3	3.8
25	213.9	190.6	23.2	0.021	53252	56.2	4.5
30	207.5	197.0	10.5	0.029	33634	59.9	4.8
35	204.9	199.6	5.3	0.042	24783	61.5	4.9
40	203.6	200.9	2.7	0.059	17536	62.3	5.0
45	203.1	201.5	1.5	0.078	12867	62.7	5.0
50	202.7	201.8	0.9	0.106	10516	62.9	5.0
55	202.6	202.0	0.5	0.140	7732	63.1	5.0
60	202.5	202.1	0.3	0.192	6359	63.1	5.0
65	202.4	202.2	0.3	0.209	6934	63.2	5.0
70	202.4	202.2	0.1	0.228	2522	63.2	5.0
75	202.4	202.2	0.1	0.243	2686	63.2	5.0
80	202.4	202.2	0.1	0.267	2952	63.2	5.0
85	202.3	202.2	0.1	0.302	3338	63.2	5.0
90	202.3	202.2	0.1	0.232	2562	63.2	5.0

The data displayed in Tables 4 and 5 are an example of one scenario that was analyzed. The data for the other scenarios, six different pipeline lengths with seven valve closure times, are listed in Appendix C.

Using Results

After reviewing the results for the steady state and transient analysis, the percent difference of the steady state and transient dynamic torques was calculated using Equation 8. The percent difference was calculated for each 5-degree valve opening. As can be seen in Table 6, the peak dynamic torque for the steady state analysis occurred at the 30-degree valve opening. The transient dynamic torque had a peak value occur shortly after the valve passed the 30-degree opening in the closing process and peaked at 15-degrees open. While it was interesting to compare the percent difference at each valve opening, a better approximation of the increase in transient torque from the steady state torque was to calculate the percent difference of the maximum steady state torque that the butterfly valve experienced to that of the maximum transient torque that the butterfly valve experienced. For the 20,000-foot pipeline being closed in 90 seconds shown in Table 6, the peak transient torque was 90,971 in-lbs and the steady state torque was 16,657 in-lbs. This resulted in a percent difference of 446%.

$$Difference\ (\%) = \frac{(90{,}971\ in.lbs. - 16{,}657\ in-lbs.)}{16{,}657\ in-lbs.} * 100 = 446\ \%$$

The butterfly valve in this system experienced 446% more dynamic torque when the valve was closed in 90 seconds due to transients than it experienced at any given point operating at steady state.

Table 6: Dynamic Torque Comparison – 90 second closure time - 20,000 ft Pipeline

Valve Open (degrees)	Transient Torque (in-lbs)	S.S. Torque (in-lbs)	% Difference
5	15521	3141	394
10	55815	7500	644
15	90971	12400	634
20	82121	15449	432
25	53252	16067	231
30	33634	16657	102
35	24783	15899	56
40	17536	14289	23
45	12867	12009	7
50	10516	10516	0
55	7732	9278	-17
60	6359	8479	-25
65	6934	6934	0
70	2522	7566	-67
75	2686	5373	-50
80	2952	2952	0
85	3338	3338	0
90	2562	2562	0

The percent difference values for each 5-degree valve opening for the other pipeline lengths and closure times are listed in the data tables found in Appendix C. Table 7 lists both the maximum transient and steady state dynamic torques and the percent difference for each valve closure increment for the 20,000-foot long pipeline. Similar tables describing the maximum dynamic torque results for each of the pipeline lengths are found in Appendix C.

The percent difference of the maximum steady state dynamic torque to the maximum transient dynamic torque for each of the test scenarios is presented in Table 8.

Table 7: Maximum Dynamic Torque - 20,000 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	135013	16657	711
54	120582	16657	624
72	104547	16657	528
90	90971	16657	446
180	61469	16657	269
270	49598	16657	198
360	42443	16657	155

As noted from the table, the larger percent difference values are found in the upper left corner of the table. Therefore, longer pipeline lengths along with smaller valve closure times created the largest percent difference in transient dynamic torque from the steady state dynamic torque for the 48-inch butterfly valve used in this experiment.

All of the percent difference values from Table 8 that are positive numbers show that there was an increase in the dynamic torque across the butterfly valve when the valve was being closed and transients were introduced into the system. Some of these values were very large differences. The same type of valve was used for each of the simulations yet the difference in dynamic torque varied greatly due to the length of the system that the valve was being used in as well as how fast the valve was being closed.

The negative percent difference values in Table 8 represent steady state dynamic torques that are slightly larger than the transient dynamic torques. This is occurring in the shorter pipeline lengths that have larger valve closure times. Under these conditions, the transient case is acting similar to the steady state case. The small differences in

Table 8: Maximum Dynamic Torque Difference (%)

	Pipeline Length (feet)					
Valve Closure Time (seconds)	**20,000**	**10,000**	**5,000**	**1,000**	**500**	**250**
36	711	498	287	60	20	4
54	624	374	190	38	12	1
72	528	305	149	27	7	-2
90	446	251	120	22	4	-2
180	269	132	55	9	-2	-5
270	198	94	43	6	-3	-5
360	155	73	35	3	-4	-6

dynamic torque are attributed to small differences in flow rate at each 5-degree valve opening between the transient case and the steady state case.

Figure 3 graphs the maximum dynamic torque data from Table 8. As can be seen from the graph, the longer pipelines have a larger percent difference in dynamic torque than the shorter pipelines. Also noted from the graph is that the smaller valve closure times create exponentially larger dynamic torque differences especially in the longer pipelines. This exponential increase is not as apparent in the shorter pipelines. The difference in dynamic torque from steady state to the transient event does not change very much in the shorter pipelines.

Butterfly valve designers, manufacturers, and operators need to be aware of the potentially large increase in dynamic torque that can occur due to transient activity. Even though the transient events may not increase the dynamic torque applied to the butterfly valve enough to damage the valve, it is increasing the dynamic torque applied to the valve and therefore should be considered in the design, manufacturing, and operation of

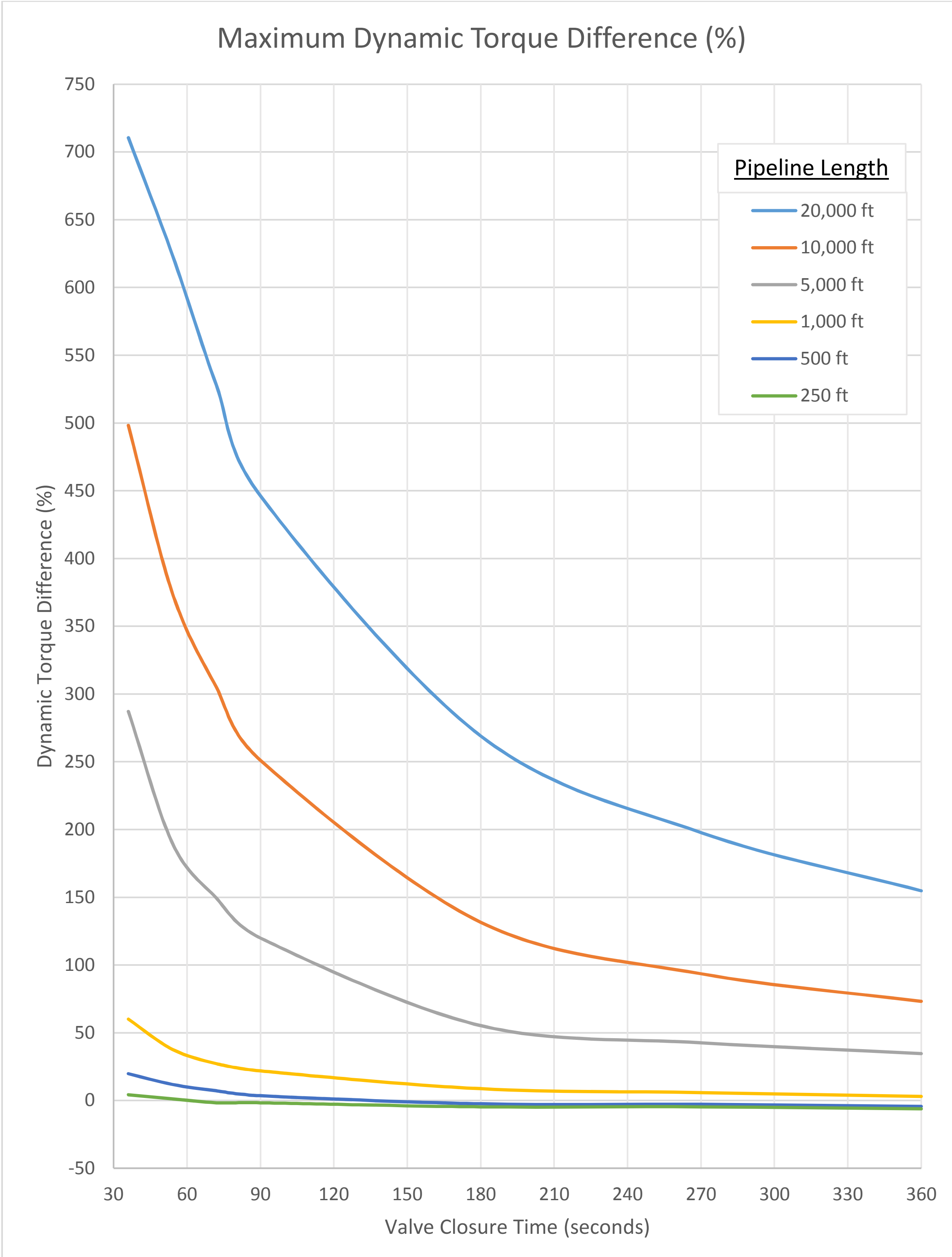

Figure 3: Maximum Dynamic Torque Difference

the valve and actuator. The increased dynamic torque during the transient event may only be applied to the butterfly valve for a short time period, yet after several occurrences of the increased torque, the valve may wear out and not perform as it was designed. If other components of the pipeline system are weaker than the butterfly valve, it is likely that they would fail first. However, if there is a chance that transient events increase the dynamic torque enough to cause failure of the valve, it is important to investigate this topic further.

IV. CONCLUSION

This research investigated the transient dynamic torque and the steady state dynamic torque in a 48-inch butterfly valve when the pipeline system length was altered as well as the closure time of the valve. This was performed in order to show that there is a variation of dynamic torque that is applied to the butterfly valve depending on the length of the pipeline and the closure time of the valve. There was a noticeably large increase in dynamic torque when the valve was being closed with long pipelines and short closure times. It was found that the transient dynamic torque applied to the 48-inch butterfly valve in the 20,000-foot long pipeline increased by over seven times that of the steady state dynamic torque when the valve was closed in 36 seconds.

The longest pipeline that was tested in this research was a 20,000 foot pipeline. The shortest valve closure time was 36 seconds with the longest being 360 seconds. The percent difference from the maximum steady state dynamic torque to the maximum transient dynamic torque for the 20,000 foot pipeline ranged from 711% larger for the 36 second closure time to 155% larger for the 360 second closure time. The percent differences decreased as the pipeline length decreased.

Although the large increase of dynamic torque during transient activity was usually only applied to the valve for a short period of time, if these events are occurring regularly, the valve could experience fatigue and possibly failure. Transient effects should be considered in the design and manufacturing of butterfly valves as well as during the operation of the valve once it is installed.

V. RECOMMENDATIONS/FURTHER RESEARCH

Although the purpose of this research was to analyze the effect that pipeline length and valve closure time had on the dynamic torque that was applied to butterfly valves, there are other related aspects that could be researched in the future. One of which would be to do a dimensional analysis of the test data in order to predict the transient torque that would result in other systems without doing a full transient analysis.

The integrity of the valve was not evaluated in this project. The amount of dynamic torque, the duration of the increased torque, as well as the fluctuating pressure differentials that this particular valve can withstand before failure occurs is unknown. All of these parameters could cause the valve to fatigue during its lifetime use and could eventually cause the valve to fail. This is something that would be beneficial to research in future projects.

REFERENCES

American Water Works Association (2012). "AWWA Manual M49: Butterfly Valves: Torque, Head Loss, and Cavitation Analysis." American Water Works Association, Denver, CO.

Flow Science (2008). "Projects: Puerto Rico Superaqueduct Pipeline Failure Hydraulic Transient Analysis." <http://www.flowscience.com/project_display.php?id=17> (November 15, 2012).

Tullis Engineering Consultants (2012). "Expert Witness Services: Hydraulic Transients, Water Hammer and Surges." <http://www.tullisengineering.com/htmlFolder/expert_witness/expert_water_hammer.htm> (November 17, 2012).

Tullis, J. P. (1989). "Hydraulics of Pipelines: Pumps, Valves, Cavitation, Transients." Wiley & Sons, New York, NY, pp. 25-26.

U.S. Army Corps of Engineers Construction Engineering Research Laboratory (2010). "Water Hammer and Mass Oscillation (WHAMO)." <http://www.cecer.army.mil/usmt/whamo/whamo.htm> (October 3, 2012).

APPENDICES

APPENDIX A: WHAMO System Input Text File

```
SYSTEM
 EL HW AT 10
 EL C1 LINK 10 15
 EL C2 LINK 15 20
 EL V LINK 20 30
 EL C3 LINK 30 35
 EL C4 LINK 35 40
 EL HBV LINK 40 50
 EL TW AT 50

 NODE 10 ELEV 0
 NODE 15 ELEV 0
 NODE 20 ELEV 0
 NODE 30 ELEV 0
 NODE 35 ELEV 0
 NODE 40 ELEV 0
 NODE 50 ELEV 0

FINI

C Element properties

RESE ID HW ELEV 32. FINI
RESE ID TW ELEV 0. FINI

CONDUIT ID C1 LENGTH 2484 DIAM 4 THICKNESS 0.375 ELASTICITY 30000000
 FRICTION 0.015 NUMSEG 150 FINI
CONDUIT ID C2 LENGTH 8 DIAM 4 THICKNESS 0.375 ELASTICITY 30000000
 FRICTION 0.015 NUMSEG 10 FINI
CONDUIT ID C3 LENGTH 24 DIAM 4 THICKNESS 0.375 ELASTICITY 30000000
 FRICTION 0.015 NUMSEG 30 FINI
CONDUIT ID C4 LENGTH 2484 DIAM 4 THICKNESS 0.375 ELASTICITY 30000000
 FRICTION 0.015 NUMSEG 150 FINI

C V IS THE Valve

VALVE ID V BUTTERFLY DIAM 4 VSCHED 1 TYPE 1 FINI
VALVE ID HBV HOWELL DIAM 4 VSCHED 2 FINI

C VALVE SCHEUDLES

SCHED VSCHED 1 TIME 0. ANGLE 0. T 90. ANGLE 90. FINI
SCHED VSCHED 2 TIME 0. GATEPOS 50. FINI

VCHAR TYPE 1 ANGLE 0. DISCOEF 1.587 A 5 DC 1.411
```

```
 A 10 DC 1.214 A 15 DC 1.089
 A 20 DC 0.973 A 25 DC 0.854 A 30 DC 0.738 A 35 DC 0.591 A 40 DC 0.473
 A 45 DC 0.366 A 50 DC 0.284 A 55 DC 0.215 A 60 DC 0.160 A 65 DC 0.122
 A 70 DC 0.084 A 75 DC 0.055 A 80 DC 0.033 A 85 DC 0.016 A 90 DC 0.0 FINISH

HIST
 NODE 10 HEAD NODE 15 PSI NODE 20 PSI NODE 30 PSI NODE 35 PSI
 NODE 40 HEAD NODE 20 Q
 FINI
PLOT
 NODE 10 HEAD NODE 15 PSI NODE 20 PSI NODE 30 PSI NODE 35 PSI
 NODE 40 HEAD NODE 20 Q
 FINI

DISPLAY ALL FINI

DISPLAY VALVE CHARACTERISTICS FINISH

SPREADSHEET
 NODE 15 PSI NODE 35 PSI
 NODE 20 Q NODE 20 Q
 FINI
C NOTE THAT AN ADDITIONAL Q IS GIVEN IN THE SPREADSHEET OUTPUT
C THIS IS BECAUSE IF NOT INCLUDED, IT DOESN'T GET OUTPUT

CONTROL
 DTCOMP .1 DTOUT 5.0 TMAX = 90
 DTCOMP .1 DTOUT 20.0 TMAX =500.
FINI
GO
GOODBYE
```

APPENDIX B: Coefficients

Table B1: Discharge Coefficients

Valve Opening (Degrees)	Discharge Coefficient C_Q	Average C_Q
5	0.016	
5	0.015	0.016
5	0.016	
10	0.033	
10	0.033	0.033
10	0.032	
15	0.055	
15	0.055	0.055
15	0.055	
20	0.084	
20	0.084	0.084
20	0.084	
25	0.122	
25	0.122	0.122
25	0.121	
30	0.160	
30	0.161	0.160
30	0.160	
35	0.215	
35	0.214	0.215
35	0.217	
40	0.284	
40	0.285	0.284
40	0.284	
45	0.366	
45	0.366	0.366
45	0.366	

Valve Opening (Degrees)	Discharge Coefficient C_Q	Average C_Q
50	0.473	
50	0.473	0.473
50	0.472	
55	0.591	
55	0.592	0.591
55	0.591	
60	0.752	
60	0.731	0.738
60	0.731	
65	0.852	
65	0.852	0.854
65	0.857	
70	0.974	
70	0.971	0.973
70	0.974	
75	1.089	
75	1.089	1.089
75	1.089	
80	1.219	
80	1.212	1.214
80	1.212	
85	1.399	
85	1.410	1.411
85	1.422	
90	1.587	
90	1.587	1.587
90	1.588	

Table B2: Torque Coefficients

Valve Open (degrees)	**$C_{t\theta}$**
5	0.002
10	0.005
15	0.010
20	0.015
25	0.021
30	0.029
35	0.042
40	0.059
45	0.078
50	0.106
55	0.140
60	0.192
65	0.209
70	0.228
75	0.243
80	0.267
85	0.302
90	0.232

APPENDIX C: Dynamic Torque Analysis Data

Table C1: Dynamic Torque Analysis – 36 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	165.5	151.8	13.7	312.1	5.3	306.8	0.002	3141	70336	2139
10	165.1	152.2	12.9	268.9	49.1	219.8	0.005	7500	127794	1604
15	164.5	152.9	11.6	222.2	95.9	126.3	0.010	12400	135013	989
20	163.5	154	9.5	189.3	128.7	60.6	0.015	15449	98546	538
25	162.3	155.3	7	171.7	146.3	25.4	0.021	16067	58302	263
30	161.4	156.2	5.2	164.4	153.5	10.9	0.029	16657	34916	110
35	160.6	157.2	3.4	161.7	156.3	5.4	0.042	15899	25251	59
40	160	157.8	2.2	160.3	157.6	2.7	0.059	14289	17536	23
45	159.6	158.2	1.4	159.7	158.2	1.5	0.078	12009	12867	7
50	159.4	158.5	0.9	159.4	158.5	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	159.2	158.7	0.5	0.140	9278	7732	-17
60	159.2	158.8	0.4	159.1	158.8	0.3	0.192	8479	6359	-25
65	159.1	158.8	0.3	159.1	158.8	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	159.0	158.9	0.1	0.228	7566	2522	-67
75	159.1	158.9	0.2	159.0	158.9	0.1	0.243	5373	2686	-50
80	159	158.9	0.1	159.0	158.9	0.1	0.267	2952	2952	0
85	159	158.9	0.1	159.0	158.9	0.1	0.302	3338	3338	0
90	159	158.9	0.1	159.0	158.9	0.1	0.232	2562	2562	0

Table C2: Dynamic Torque Analysis – 54 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	165.5	151.8	13.7	248.1	68.8	179.3	0.002	3141	41106	1209
10	165.1	152.2	12.9	243.7	73.8	169.9	0.005	7500	98781	1217
15	164.5	152.9	11.6	215.3	102.5	112.8	0.010	12400	120582	872
20	163.5	154	9.5	187.6	130.2	57.4	0.015	15449	93342	504
25	162.3	155.3	7	171.3	146.6	24.7	0.021	16067	56695	253
30	161.4	156.2	5.2	164.4	153.5	10.9	0.029	16657	34916	110
35	160.6	157.2	3.4	161.6	156.3	5.3	0.042	15899	24783	56
40	160	157.8	2.2	160.3	157.6	2.7	0.059	14289	17536	23
45	159.6	158.2	1.4	159.7	158.2	1.5	0.078	12009	12867	7
50	159.4	158.5	0.9	159.4	158.5	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	159.2	158.7	0.5	0.140	9278	7732	-17
60	159.2	158.8	0.4	159.1	158.8	0.3	0.192	8479	6359	-25
65	159.1	158.8	0.3	159.1	158.8	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	159.1	158.9	0.2	0.228	7566	5044	-33
75	159.1	158.9	0.2	159.0	158.9	0.1	0.243	5373	2686	-50
80	159	158.9	0.1	159.0	158.9	0.1	0.267	2952	2952	0
85	159	158.9	0.1	159.0	158.9	0.1	0.302	3338	3338	0
90	159	158.9	0.1	159.0	158.9	0.1	0.232	2562	2562	0

Table C3: Dynamic Torque Analysis – 72 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	165.5	151.8	13.7	210.4	106.7	103.7	0.002	3141	23774	657
10	165.1	152.2	12.9	222.0	95.2	126.8	0.005	7500	73723	883
15	164.5	152.9	11.6	207.7	109.9	97.8	0.010	12400	104547	743
20	163.5	154	9.5	185.9	131.9	54	0.015	15449	87813	468
25	162.3	155.3	7	170.9	146.9	24	0.021	16067	55089	243
30	161.4	156.2	5.2	164.3	153.6	10.7	0.029	16657	34275	106
35	160.6	157.2	3.4	161.6	156.3	5.3	0.042	15899	24783	56
40	160	157.8	2.2	160.3	157.6	2.7	0.059	14289	17536	23
45	159.6	158.2	1.4	159.7	158.2	1.5	0.078	12009	12867	7
50	159.4	158.5	0.9	159.4	158.5	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	159.2	158.7	0.5	0.140	9278	7732	-17
60	159.2	158.8	0.4	159.1	158.8	0.3	0.192	8479	6359	-25
65	159.1	158.8	0.3	159.1	158.8	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	159.1	158.9	0.2	0.228	7566	5044	-33
75	159.1	158.9	0.2	159.0	158.9	0.1	0.243	5373	2686	-50
80	159	158.9	0.1	159.0	158.9	0.1	0.267	2952	2952	0
85	159	158.9	0.1	159.0	158.9	0.1	0.302	3338	3338	0
90	159	158.9	0.1	159.0	158.9	0.1	0.232	2562	2562	0

Table C4: Dynamic Torque Analysis – 90 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**Transient Torque (in-lbs)**	**S.S. Torque (in-lbs)**	**% Difference**
5	165.5	151.8	13.7	235.8	168.1	67.7	0.002	15521	3141	394
10	165.1	152.2	12.9	250.0	153.9	96	0.005	55815	7500	644
15	164.5	152.9	11.6	244.6	159.5	85.1	0.010	90971	12400	634
20	163.5	154	9.5	227.5	176.9	50.5	0.015	82121	15449	432
25	162.3	155.3	7	213.9	190.6	23.2	0.021	53252	16067	231
30	161.4	156.2	5.2	207.5	197.0	10.5	0.029	33634	16657	102
35	160.6	157.2	3.4	204.9	199.6	5.3	0.042	24783	15899	56
40	160	157.8	2.2	203.6	200.9	2.7	0.059	17536	14289	23
45	159.6	158.2	1.4	203.1	201.5	1.5	0.078	12867	12009	7
50	159.4	158.5	0.9	202.7	201.8	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	202.6	202.0	0.5	0.140	7732	9278	-17
60	159.2	158.8	0.4	202.5	202.1	0.3	0.192	6359	8479	-25
65	159.1	158.8	0.3	202.4	202.2	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	202.4	202.2	0.1	0.228	2522	7566	-67
75	159.1	158.9	0.2	202.4	202.2	0.1	0.243	2686	5373	-50
80	159	158.9	0.1	202.4	202.2	0.1	0.267	2952	2952	0
85	159	158.9	0.1	202.3	202.2	0.1	0.302	3338	3338	0
90	159	158.9	0.1	202.3	202.2	0.1	0.232	2562	2562	0

Table C5: Dynamic Torque Analysis – 180 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	165.5	151.8	13.7	169.4	147.9	21.5	0.002	3141	4929	57
10	165.1	152.2	12.9	179.5	137.8	41.7	0.005	7500	24245	223
15	164.5	152.9	11.6	182.8	134.5	48.3	0.010	12400	51632	316
20	163.5	154	9.5	177.7	139.9	37.8	0.015	15449	61469	298
25	162.3	155.3	7	169.1	148.6	20.5	0.021	16067	47055	193
30	161.4	156.2	5.2	163.8	154.0	9.8	0.029	16657	31392	88
35	160.6	157.2	3.4	161.5	156.4	5.1	0.042	15899	23848	50
40	160	157.8	2.2	160.3	157.6	2.7	0.059	14289	17536	23
45	159.6	158.2	1.4	159.7	158.2	1.5	0.078	12009	12867	7
50	159.4	158.5	0.9	159.4	158.5	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	159.2	158.7	0.5	0.140	9278	7732	-17
60	159.2	158.8	0.4	159.1	158.8	0.3	0.192	8479	6359	-25
65	159.1	158.8	0.3	159.1	158.8	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	159.1	158.9	0.2	0.228	7566	5044	-33
75	159.1	158.9	0.2	159.0	158.9	0.1	0.243	5373	2686	-50
80	159	158.9	0.1	159.0	158.9	0.1	0.267	2952	2952	0
85	159	158.9	0.1	159.0	158.9	0.1	0.302	3338	3338	0
90	159	158.9	0.1	159.0	158.9	0.1	0.232	2562	2562	0

Table C6: Dynamic Torque Analysis – 270 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	165.5	151.8	13.7	167.2	150.1	17.1	0.002	3141	3920	25
10	165.1	152.2	12.9	173.2	144.1	29.1	0.005	7500	16919	126
15	164.5	152.9	11.6	175.8	141.6	34.2	0.010	12400	36559	195
20	163.5	154	9.5	174.0	143.5	30.5	0.015	15449	49598	221
25	162.3	155.3	7	168.0	149.7	18.3	0.021	16067	42005	161
30	161.4	156.2	5.2	163.5	154.3	9.2	0.029	16657	29470	77
35	160.6	157.2	3.4	161.4	156.4	5	0.042	15899	23381	47
40	160	157.8	2.2	160.2	157.6	2.6	0.059	14289	16887	18
45	159.6	158.2	1.4	159.7	158.2	1.5	0.078	12009	12867	7
50	159.4	158.5	0.9	159.4	158.5	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	159.2	158.7	0.5	0.140	9278	7732	-17
60	159.2	158.8	0.4	159.1	158.8	0.3	0.192	8479	6359	-25
65	159.1	158.8	0.3	159.1	158.8	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	159.1	158.9	0.2	0.228	7566	5044	-33
75	159.1	158.9	0.2	159.0	158.9	0.1	0.243	5373	2686	-50
80	159	158.9	0.1	159.0	158.9	0.1	0.267	2952	2952	0
85	159	158.9	0.1	159.0	158.9	0.1	0.302	3338	3338	0
90	159	158.9	0.1	159.0	158.9	0.1	0.232	2562	2562	0

Table C7: Dynamic Torque Analysis – 360 second closure time - 20,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	165.5	151.8	13.7	166.9	150.4	16.5	0.002	3141	3783	20
10	165.1	152.2	12.9	170.7	146.6	24.1	0.005	7500	14012	87
15	164.5	152.9	11.6	172.4	144.9	27.5	0.010	12400	29397	137
20	163.5	154	9.5	171.8	145.7	26.1	0.015	15449	42443	175
25	162.3	155.3	7	167.2	150.4	16.8	0.021	16067	38562	140
30	161.4	156.2	5.2	163.3	154.5	8.8	0.029	16657	28189	69
35	160.6	157.2	3.4	161.3	156.5	4.8	0.042	15899	22445	41
40	160	157.8	2.2	160.2	157.6	2.6	0.059	14289	16887	18
45	159.6	158.2	1.4	159.7	158.2	1.5	0.078	12009	12867	7
50	159.4	158.5	0.9	159.4	158.5	0.9	0.106	10516	10516	0
55	159.2	158.6	0.6	159.2	158.7	0.5	0.140	9278	7732	-17
60	159.2	158.8	0.4	159.1	158.8	0.3	0.192	8479	6359	-25
65	159.1	158.8	0.3	159.1	158.8	0.3	0.209	6934	6934	0
70	159.1	158.8	0.3	159.1	158.9	0.2	0.228	7566	5044	-33
75	159.1	158.9	0.2	159.0	158.9	0.1	0.243	5373	2686	-50
80	159	158.9	0.1	159.0	158.9	0.1	0.267	2952	2952	0
85	159	158.9	0.1	159.0	158.9	0.1	0.302	3338	3338	0
90	159	158.9	0.1	159.0	158.9	0.1	0.232	2562	2562	0

Table C8: Maximum Dynamic Torque - 20,000 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	135013	16657	711
54	120582	16657	624
72	104547	16657	528
90	90971	16657	446
180	61469	16657	269
270	49598	16657	198
360	42443	16657	155

Table C9: Dynamic Torque Analysis – 36 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	100.5	86.8	13.7	142.7	44.3	98.4	0.002	3141	22559	618
10	100.3	87.0	13.3	169.2	17.8	151.4	0.005	7733	88025	1038
15	100.0	87.4	12.6	163.2	24.5	138.7	0.010	13469	148269	1001
20	99.3	88.2	11.1	137.4	50.8	86.6	0.015	18050	140826	680
25	98.4	89.3	9.1	114.8	73.5	41.3	0.021	20888	94798	354
30	97.6	90.3	7.3	103.7	84.7	19	0.029	23384	60862	160
35	96.7	91.4	5.3	99.1	89.4	9.7	0.042	24783	45358	83
40	95.9	92.3	3.6	96.7	91.7	5	0.059	23382	32475	39
45	95.4	92.9	2.5	95.7	92.8	2.9	0.078	21445	24876	16
50	95.0	93.4	1.6	95.1	93.4	1.7	0.106	18696	19864	6
55	94.7	93.7	1	94.7	93.7	1	0.140	15464	15464	0
60	94.6	93.9	0.7	94.6	93.9	0.7	0.192	14838	14838	0
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.3	94.1	0.2	0.267	8855	5903	-33
85	94.4	94.1	0.3	94.3	94.1	0.2	0.302	10015	6677	-33
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C10: Dynamic Torque Analysis – 54 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	100.5	86.8	13.7	116.6	70.6	46	0.002	3141	10546	236
10	100.3	87.0	13.3	134.9	52.4	82.5	0.005	7733	47966	520
15	100.0	87.4	12.6	142.5	45	97.5	0.010	13469	104226	674
20	99.3	88.2	11.1	130.1	57.8	72.3	0.015	18050	117572	551
25	98.4	89.3	9.1	113.1	75.1	38	0.021	20888	87224	318
30	97.6	90.3	7.3	103.3	85	18.3	0.029	23384	58620	151
35	96.7	91.4	5.3	98.9	89.5	9.4	0.042	24783	43956	77
40	95.9	92.3	3.6	96.6	91.8	4.8	0.059	23382	31176	33
45	95.4	92.9	2.5	95.7	92.8	2.9	0.078	21445	24876	16
50	95.0	93.4	1.6	95.1	93.4	1.7	0.106	18696	19864	6
55	94.7	93.7	1	94.7	93.8	0.9	0.140	15464	13917	-10
60	94.6	93.9	0.7	94.5	93.9	0.6	0.192	14838	12719	-14
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.3	94.1	0.2	0.267	8855	5903	-33
85	94.4	94.1	0.3	94.3	94.1	0.2	0.302	10015	6677	-33
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C11: Dynamic Torque Analysis – 72 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	100.5	86.8	13.7	107.9	79.3	28.6	0.002	3141	6557	109
10	100.3	87.0	13.3	121.7	65.6	56.1	0.005	7733	32617	322
15	100.0	87.4	12.6	130.1	57.3	72.8	0.010	13469	77822	478
20	99.3	88.2	11.1	124.7	63	61.7	0.015	18050	100334	456
25	98.4	89.3	9.1	111.6	76.5	35.1	0.021	20888	80567	286
30	97.6	90.3	7.3	102.9	85.4	17.5	0.029	23384	56057	140
35	96.7	91.4	5.3	98.8	89.5	9.3	0.042	24783	43488	75
40	95.9	92.3	3.6	96.6	91.8	4.8	0.059	23382	31176	33
45	95.4	92.9	2.5	95.6	92.8	2.8	0.078	21445	24019	12
50	95.0	93.4	1.6	95.1	93.4	1.7	0.106	18696	19864	6
55	94.7	93.7	1	94.7	93.8	0.9	0.140	15464	13917	-10
60	94.6	93.9	0.7	94.5	93.9	0.6	0.192	14838	12719	-14
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.4	94.1	0.3	0.267	8855	8855	0
85	94.4	94.1	0.3	94.3	94.1	0.2	0.302	10015	6677	-33
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C12: Dynamic Torque Analysis – 90 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	100.5	86.8	13.7	104.3	82.9	21.4	0.002	3141	4906	56
10	100.3	87.0	13.3	115.2	72.1	43.1	0.005	7733	25059	224
15	100.0	87.4	12.6	122.5	64.8	57.7	0.010	13469	61681	358
20	99.3	88.2	11.1	120.6	67.1	53.5	0.015	18050	87000	382
25	98.4	89.3	9.1	110.3	77.7	32.6	0.021	20888	74829	258
30	97.6	90.3	7.3	102.5	85.7	16.8	0.029	23384	53815	130
35	96.7	91.4	5.3	98.7	89.6	9.1	0.042	24783	42553	72
40	95.9	92.3	3.6	96.6	91.8	4.8	0.059	23382	31176	33
45	95.4	92.9	2.5	95.6	92.8	2.8	0.078	21445	24019	12
50	95.0	93.4	1.6	95.1	93.4	1.7	0.106	18696	19864	6
55	94.7	93.7	1	94.7	93.7	1	0.140	15464	15464	0
60	94.6	93.9	0.7	94.5	93.9	0.6	0.192	14838	12719	-14
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.4	94.1	0.3	0.267	8855	8855	0
85	94.4	94.1	0.3	94.3	94.1	0.2	0.302	10015	6677	-33
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C13: Dynamic Torque Analysis – 180 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	100.5	86.8	13.7	101.9	85.4	16.5	0.002	3141	3783	20
10	100.3	87.0	13.3	105.9	81.4	24.5	0.005	7733	14245	84
15	100.0	87.4	12.6	108.6	78.7	29.9	0.010	13469	31963	137
20	99.3	88.2	11.1	110.3	77.2	33.1	0.015	18050	53826	198
25	98.4	89.3	9.1	106.4	81.4	25	0.021	20888	57384	175
30	97.6	90.3	7.3	101.3	86.8	14.5	0.029	23384	46447	99
35	96.7	91.4	5.3	98.3	89.9	8.4	0.042	24783	39280	58
40	95.9	92.3	3.6	96.5	91.9	4.6	0.059	23382	29877	28
45	95.4	92.9	2.5	95.6	92.8	2.8	0.078	21445	24019	12
50	95.0	93.4	1.6	95	93.4	1.6	0.106	18696	18696	0
55	94.7	93.7	1	94.7	93.7	1	0.140	15464	15464	0
60	94.6	93.9	0.7	94.5	93.9	0.6	0.192	14838	12719	-14
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.3	94.1	0.2	0.267	8855	5903	-33
85	94.4	94.1	0.3	94.3	94.1	0.2	0.302	10015	6677	-33
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C14: Dynamic Torque Analysis – 270 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	100.5	86.8	13.7	101.5	85.8	15.7	0.002	3141	3599	15
10	100.3	87.0	13.3	103.8	83.5	20.3	0.005	7733	11803	53
15	100.0	87.4	12.6	105	82.3	22.7	0.010	13469	24266	80
20	99.3	88.2	11.1	106.4	81	25.4	0.015	18050	41305	129
25	98.4	89.3	9.1	104.3	83.4	20.9	0.021	20888	47973	130
30	97.6	90.3	7.3	100.5	87.5	13	0.029	23384	41643	78
35	96.7	91.4	5.3	98.1	90.1	8	0.042	24783	37409	51
40	95.9	92.3	3.6	96.4	91.9	4.5	0.059	23382	29227	25
45	95.4	92.9	2.5	95.6	92.8	2.8	0.078	21445	24019	12
50	95.0	93.4	1.6	95	93.4	1.6	0.106	18696	18696	0
55	94.7	93.7	1	94.7	93.7	1	0.140	15464	15464	0
60	94.6	93.9	0.7	94.5	93.9	0.6	0.192	14838	12719	-14
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.3	94.1	0.2	0.267	8855	5903	-33
85	94.4	94.1	0.3	94.3	94.1	0.2	0.302	10015	6677	-33
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C15: Dynamic Torque Analysis – 360 second closure time - 10,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	100.5	86.8	13.7	101.2	86	15.2	0.002	3141	3485	11
10	100.3	87.0	13.3	102.9	84.4	18.5	0.005	7733	10756	39
15	100.0	87.4	12.6	103.5	83.8	19.7	0.010	13469	21059	56
20	99.3	88.2	11.1	104.6	82.9	21.7	0.015	18050	35288	95
25	98.4	89.3	9.1	103.2	84.5	18.7	0.021	20888	42923	105
30	97.6	90.3	7.3	100.1	87.9	12.2	0.029	23384	39080	67
35	96.7	91.4	5.3	97.9	90.3	7.6	0.042	24783	35539	43
40	95.9	92.3	3.6	96.3	92	4.3	0.059	23382	27928	19
45	95.4	92.9	2.5	95.5	92.8	2.7	0.078	21445	23161	8
50	95.0	93.4	1.6	95	93.4	1.6	0.106	18696	18696	0
55	94.7	93.7	1	94.7	93.7	1	0.140	15464	15464	0
60	94.6	93.9	0.7	94.5	93.9	0.6	0.192	14838	12719	-14
65	94.5	94.0	0.5	94.5	94	0.5	0.209	11556	11556	0
70	94.4	94.0	0.4	94.4	94.1	0.3	0.228	10088	7566	-25
75	94.4	94.1	0.3	94.4	94.1	0.3	0.243	8059	8059	0
80	94.4	94.1	0.3	94.4	94.1	0.3	0.267	8855	8855	0
85	94.4	94.1	0.3	94.3	94.2	0.1	0.302	10015	3338	-67
90	94.3	94.1	0.2	94.3	94.1	0.2	0.232	5124	5124	0

Table C16: Maximum Dynamic Torque - 10,000 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	148269	24783	498
54	117572	24783	374
72	100334	24783	305
90	87000	24783	251
180	57384	24783	132
270	47973	24783	94
360	42923	24783	73

Table C17: Dynamic Torque Analysis – 36 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	64.3	36	28.3	0.002	3164	6488	105
10	57.0	43.5	13.5	79.1	21.4	57.7	0.005	7849	33547	327
15	56.8	43.8	13	92.8	7.8	85	0.010	13897	90864	554
20	56.4	44.3	12.1	92.3	8.8	83.5	0.015	19677	135785	590
25	55.8	45.1	10.7	77.5	24.3	53.2	0.021	24560	122113	397
30	55.2	46.0	9.2	65.2	36.9	28.3	0.029	29470	90653	208
35	54.4	47.1	7.3	58.9	43.4	15.5	0.042	34136	72480	112
40	53.6	48.2	5.4	55.3	47.1	8.2	0.059	35073	53259	52
45	52.9	49.1	3.8	53.7	48.8	4.9	0.078	32597	42033	29
50	52.4	49.8	2.6	52.7	49.8	2.9	0.106	30381	33886	12
55	52.1	50.3	1.8	52.1	50.4	1.7	0.140	27835	26288	-6
60	51.8	50.6	1.2	51.8	50.7	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.7	50.9	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.6	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	51.5	51.1	0.4	0.232	10247	10247	0

Table C18: Dynamic Torque Analysis – 54 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	59.5	41	18.5	0.002	3164	4241	34
10	57.0	43.5	13.5	68.5	32	36.5	0.005	7849	21221	170
15	56.8	43.8	13	76.7	23.9	52.8	0.010	13897	56443	306
20	56.4	44.3	12.1	80.6	20.4	60.2	0.015	19677	97895	398
25	55.8	45.1	10.7	72.9	28.6	44.3	0.021	24560	101684	314
30	55.2	46.0	9.2	63.7	38.2	25.5	0.029	29470	81684	177
35	54.4	47.1	7.3	58.4	43.8	14.6	0.042	34136	68272	100
40	53.6	48.2	5.4	55.2	47.2	8	0.059	35073	51960	48
45	52.9	49.1	3.8	53.6	48.8	4.8	0.078	32597	41175	26
50	52.4	49.8	2.6	52.7	49.8	2.9	0.106	30381	33886	12
55	52.1	50.3	1.8	52.1	50.4	1.7	0.140	27835	26288	-6
60	51.8	50.6	1.2	51.8	50.7	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.7	50.9	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.6	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	51.5	51.1	0.4	0.232	10247	10247	0

Table C19: Dynamic Torque Analysis – 72 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	58.7	41.7	17	0.002	3164	3897	23
10	57.0	43.5	13.5	64.5	36	28.5	0.005	7849	16570	111
15	56.8	43.8	13	69.7	30.9	38.8	0.010	13897	41477	198
20	56.4	44.3	12.1	73.9	26.9	47	0.015	19677	76430	288
25	55.8	45.1	10.7	69.7	31.6	38.1	0.021	24560	87453	256
30	55.2	46.0	9.2	62.6	39.2	23.4	0.029	29470	74957	154
35	54.4	47.1	7.3	58	44.1	13.9	0.042	34136	64998	90
40	53.6	48.2	5.4	55	47.3	7.7	0.059	35073	50011	43
45	52.9	49.1	3.8	53.6	48.8	4.8	0.078	32597	41175	26
50	52.4	49.8	2.6	52.7	49.8	2.9	0.106	30381	33886	12
55	52.1	50.3	1.8	52.1	50.4	1.7	0.140	27835	26288	-6
60	51.8	50.6	1.2	51.8	50.7	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.7	50.9	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.6	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	51.5	51.1	0.4	0.232	10247	10247	0

Table C20: Dynamic Torque Analysis – 90 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	58.5	42	16.5	0.002	3164	3783	20
10	57.0	43.5	13.5	62.5	37.9	24.6	0.005	7849	14303	82
15	56.8	43.8	13	66	34.5	31.5	0.010	13897	33673	142
20	56.4	44.3	12.1	69.9	30.9	39	0.015	19677	63420	222
25	55.8	45.1	10.7	67.4	33.8	33.6	0.021	24560	77124	214
30	55.2	46.0	9.2	61.7	40	21.7	0.029	29470	69511	136
35	54.4	47.1	7.3	57.7	44.3	13.4	0.042	34136	62660	84
40	53.6	48.2	5.4	54.9	47.3	7.6	0.059	35073	49362	41
45	52.9	49.1	3.8	53.5	48.9	4.6	0.078	32597	39459	21
50	52.4	49.8	2.6	52.7	49.8	2.9	0.106	30381	33886	12
55	52.1	50.3	1.8	52.1	50.4	1.7	0.140	27835	26288	-6
60	51.8	50.6	1.2	51.8	50.7	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.7	50.9	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.6	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	51.5	51.1	0.4	0.232	10247	10247	0

Table C21: Dynamic Torque Analysis – 180 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	59.5	41	15.2	0.002	3164	3485	10
10	57.0	43.5	13.5	60.3	40.2	18.5	0.005	7849	10756	37
15	56.8	43.8	13	62.2	38.5	20.1	0.010	13897	21487	55
20	56.4	44.3	12.1	62.1	38.9	23.7	0.015	19677	38540	96
25	55.8	45.1	10.7	59.2	42.2	23.2	0.021	24560	53252	117
30	55.2	46.0	9.2	56.7	45.1	17	0.029	29470	54456	85
35	54.4	47.1	7.3	54.6	47.6	11.6	0.042	34136	54243	59
40	53.6	48.2	5.4	53.4	48.9	7	0.059	35073	45465	30
45	52.9	49.1	3.8	52.6	49.8	4.5	0.078	32597	38601	18
50	52.4	49.8	2.6	52.1	50.4	2.8	0.106	30381	32718	8
55	52.1	50.3	1.8	51.8	50.7	1.7	0.140	27835	26288	-6
60	51.8	50.6	1.2	51.7	50.9	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.6	51	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.5	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51.1	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	43.3	43.3	0.4	0.232	10247	10247	0

Table C22: Dynamic Torque Analysis – 270 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	57.6	42.9	14.7	0.002	3164	3370	7
10	57.0	43.5	13.5	58.7	41.8	16.9	0.005	7849	9826	25
15	56.8	43.8	13	59	41.5	17.5	0.010	13897	18707	35
20	56.4	44.3	12.1	60	40.6	19.4	0.015	19677	31548	60
25	55.8	45.1	10.7	60.1	40.8	19.3	0.021	24560	44300	80
30	55.2	46.0	9.2	58.1	43.2	14.9	0.029	29470	47729	62
35	54.4	47.1	7.3	56.2	45.5	10.7	0.042	34136	50035	47
40	53.6	48.2	5.4	54.3	47.7	6.6	0.059	35073	42867	22
45	52.9	49.1	3.8	53.3	49	4.3	0.078	32597	36886	13
50	52.4	49.8	2.6	52.5	49.8	2.7	0.106	30381	31549	4
55	52.1	50.3	1.8	52.1	50.4	1.7	0.140	27835	26288	-6
60	51.8	50.6	1.2	51.8	50.7	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.7	50.9	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.6	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	51.5	51.1	0.4	0.232	10247	10247	0

Table C23: Dynamic Torque Analysis – 360 second closure time - 5,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.1	43.3	13.8	57.5	43	14.5	0.002	3164	3324	5
10	57.0	43.5	13.5	58.3	42.2	16.1	0.005	7849	9361	19
15	56.8	43.8	13	58.4	42.1	16.3	0.010	13897	17424	25
20	56.4	44.3	12.1	59.1	41.5	17.6	0.015	19677	28621	45
25	55.8	45.1	10.7	59.1	41.8	17.3	0.021	24560	39710	62
30	55.2	46.0	9.2	57.5	43.8	13.7	0.029	29470	43885	49
35	54.4	47.1	7.3	55.9	45.8	10.1	0.042	34136	47229	38
40	53.6	48.2	5.4	54.2	47.8	6.4	0.059	35073	41568	19
45	52.9	49.1	3.8	53.2	49	4.2	0.078	32597	36028	11
50	52.4	49.8	2.6	52.5	49.9	2.6	0.106	30381	30381	0
55	52.1	50.3	1.8	52	50.4	1.6	0.140	27835	24742	-11
60	51.8	50.6	1.2	51.8	50.7	1.1	0.192	25437	23317	-8
65	51.7	50.8	0.9	51.7	50.9	0.8	0.209	20801	18490	-11
70	51.6	50.9	0.7	51.6	51	0.6	0.228	17655	15132	-14
75	51.6	51.0	0.6	51.5	51	0.5	0.243	16119	13432	-17
80	51.5	51.1	0.4	51.5	51.1	0.4	0.267	11807	11807	0
85	51.5	51.1	0.4	51.5	51.1	0.4	0.302	13354	13354	0
90	51.5	51.1	0.4	51.5	51.1	0.4	0.232	10247	10247	0

Table C24: Maximum Dynamic Torque - 5,000 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	135785	35073	287
54	101684	35073	190
72	87453	35073	149
90	77124	35073	120
180	54456	35073	55
270	50035	35073	43
360	47229	35073	35

Table C25: Dynamic Torque Analysis – 36 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	57.2	43.3	13.9	57.8	42.6	15.2	0.002	3187	3485	9
10	57.1	43.4	13.7	59.5	41	18.5	0.005	7965	10756	35
15	57.1	43.5	13.6	60.4	40.1	20.3	0.010	14538	21700	49
20	57.0	43.8	13.2	63.1	37.5	25.6	0.015	21465	41630	94
25	56.7	44.3	12.4	65.1	36	29.1	0.021	28462	66795	135
30	56.5	44.9	11.6	63.8	38.1	25.7	0.029	37158	82324	122
35	56.1	45.8	10.3	61.9	41.1	20.8	0.042	48164	97264	102
40	55.6	47.0	8.6	59	44.9	14.1	0.059	55857	91579	64
45	55.1	48.2	6.9	57.1	47.4	9.7	0.078	59189	83207	41
50	54.6	49.4	5.2	55.7	49.4	6.3	0.106	60761	73614	21
55	54.2	50.3	3.9	54.6	50.7	3.9	0.140	60309	60309	0
60	53.9	51.1	2.8	54	51.5	2.5	0.192	59353	52994	-11
65	53.7	51.5	2.2	53.7	51.9	1.8	0.209	50848	41603	-18
70	53.6	51.8	1.8	53.6	52.1	1.5	0.228	45397	37831	-17
75	53.5	52.0	1.5	53.5	52.3	1.2	0.243	40297	32238	-20
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C26: Dynamic Torque Analysis – 54 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.6	42.9	14.7	0.002	3187	3370	6
10	57.1	43.4	13.7	58.6	41.8	16.8	0.005	7965	9768	23
15	57.1	43.5	13.6	59.1	41.5	17.6	0.010	14538	18814	29
20	57.0	43.8	13.2	60.5	40.1	20.4	0.015	21465	33174	55
25	56.7	44.3	12.4	61.9	39.1	22.8	0.021	28462	52334	84
30	56.5	44.9	11.6	61.2	40.4	20.8	0.029	37158	66628	79
35	56.1	45.8	10.3	60.2	42.3	17.9	0.042	48164	83703	74
40	55.6	47.0	8.6	58.1	45.4	12.7	0.059	55857	82486	48
45	55.1	48.2	6.9	56.7	47.6	9.1	0.078	59189	78061	32
50	54.6	49.4	5.2	55.5	49.4	6.1	0.106	60761	71277	17
55	54.2	50.3	3.9	54.5	50.7	3.8	0.140	60309	58762	-3
60	53.9	51.1	2.8	54	51.5	2.5	0.192	59353	52994	-11
65	53.7	51.5	2.2	53.7	51.8	1.9	0.209	50848	43914	-14
70	53.6	51.8	1.8	53.6	52.1	1.5	0.228	45397	37831	-17
75	53.5	52.0	1.5	53.4	52.3	1.1	0.243	40297	29551	-27
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C27: Dynamic Torque Analysis – 72 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.5	43	14.5	0.002	3187	3324	4
10	57.1	43.4	13.7	58.3	42.2	16.1	0.005	7965	9361	18
15	57.1	43.5	13.6	58.5	42	16.5	0.010	14538	17638	21
20	57.0	43.8	13.2	59.4	41.2	18.2	0.015	21465	29596	38
25	56.7	44.3	12.4	60.4	40.5	19.9	0.021	28462	45678	60
30	56.5	44.9	11.6	59.9	41.6	18.3	0.029	37158	58620	58
35	56.1	45.8	10.3	59.3	43.1	16.2	0.042	48164	75753	57
40	55.6	47.0	8.6	57.6	45.7	11.9	0.059	55857	77290	38
45	55.1	48.2	6.9	56.4	47.7	8.7	0.078	59189	74629	26
50	54.6	49.4	5.2	55.3	49.4	5.9	0.106	60761	68940	13
55	54.2	50.3	3.9	54.5	50.7	3.8	0.140	60309	58762	-3
60	53.9	51.1	2.8	53.9	51.4	2.5	0.192	59353	52994	-11
65	53.7	51.5	2.2	53.7	51.8	1.9	0.209	50848	43914	-14
70	53.6	51.8	1.8	53.6	52.1	1.5	0.228	45397	37831	-17
75	53.5	52.0	1.5	53.4	52.3	1.1	0.243	40297	29551	-27
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C28: Dynamic Torque Analysis – 90 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.4	43	14.4	0.002	3187	3301	4
10	57.1	43.4	13.7	58	42.5	15.5	0.005	7965	9012	13
15	57.1	43.5	13.6	58.2	42.3	15.9	0.010	14538	16997	17
20	57.0	43.8	13.2	58.9	41.7	17.2	0.015	21465	27970	30
25	56.7	44.3	12.4	59.6	41.3	18.3	0.021	28462	42005	48
30	56.5	44.9	11.6	59.2	42.2	17	0.029	37158	54456	47
35	56.1	45.8	10.3	58.7	43.5	15.2	0.042	48164	71077	48
40	55.6	47.0	8.6	57.3	45.9	11.4	0.059	55857	74043	33
45	55.1	48.2	6.9	56.2	47.8	8.4	0.078	59189	72056	22
50	54.6	49.4	5.2	55.2	49.4	5.8	0.106	60761	67772	12
55	54.2	50.3	3.9	54.4	50.7	3.7	0.140	60309	57216	-5
60	53.9	51.1	2.8	53.9	51.4	2.5	0.192	59353	52994	-11
65	53.7	51.5	2.2	53.7	51.8	1.9	0.209	50848	43914	-14
70	53.6	51.8	1.8	53.5	52.1	1.4	0.228	45397	35309	-22
75	53.5	52.0	1.5	53.4	52.2	1.2	0.243	40297	32238	-20
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C29: Dynamic Torque Analysis – 180 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.3	43.2	14.1	0.002	3187	3233	1
10	57.1	43.4	13.7	57.6	42.9	14.7	0.005	7965	8547	7
15	57.1	43.5	13.6	57.6	42.9	14.7	0.010	14538	15714	8
20	57.0	43.8	13.2	57.9	42.7	15.2	0.015	21465	24718	15
25	56.7	44.3	12.4	58.2	42.7	15.5	0.021	28462	35578	25
30	56.5	44.9	11.6	57.8	43.5	14.3	0.029	37158	45807	23
35	56.1	45.8	10.3	57.5	44.5	13	0.042	48164	60790	26
40	55.6	47.0	8.6	56.5	46.4	10.1	0.059	55857	65599	17
45	55.1	48.2	6.9	55.7	48	7.7	0.078	59189	66051	12
50	54.6	49.4	5.2	54.9	49.5	5.4	0.106	60761	63098	4
55	54.2	50.3	3.9	54.3	50.7	3.6	0.140	60309	55669	-8
60	53.9	51.1	2.8	53.9	51.4	2.5	0.192	59353	52994	-11
65	53.7	51.5	2.2	53.6	51.8	1.8	0.209	50848	41603	-18
70	53.6	51.8	1.8	53.5	52	1.5	0.228	45397	37831	-17
75	53.5	52.0	1.5	53.4	52.2	1.2	0.243	40297	32238	-20
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C30: Dynamic Torque Analysis – 270 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.2	14	0.002	3187	3210	1
10	57.1	43.4	13.7	57.4	43	14.4	0.005	7965	8372	5
15	57.1	43.5	13.6	57.5	43	14.5	0.010	14538	15500	7
20	57.0	43.8	13.2	57.6	43	14.6	0.015	21465	23742	11
25	56.7	44.3	12.4	57.7	43.1	14.6	0.021	28462	33512	18
30	56.5	44.9	11.6	57.4	43.9	13.5	0.029	37158	43244	16
35	56.1	45.8	10.3	57.1	44.8	12.3	0.042	48164	57516	19
40	55.6	47.0	8.6	56.2	46.5	9.7	0.059	55857	63001	13
45	55.1	48.2	6.9	55.5	48	7.5	0.078	59189	64336	9
50	54.6	49.4	5.2	54.8	49.5	5.3	0.106	60761	61930	2
55	54.2	50.3	3.9	54.2	50.6	3.6	0.140	60309	55669	-8
60	53.9	51.1	2.8	53.8	51.4	2.4	0.192	59353	50874	-14
65	53.7	51.5	2.2	53.6	51.8	1.8	0.209	50848	41603	-18
70	53.6	51.8	1.8	53.5	52	1.5	0.228	45397	37831	-17
75	53.5	52.0	1.5	53.4	52.2	1.2	0.243	40297	32238	-20
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C31: Dynamic Torque Analysis – 360 second closure time - 1,000 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.2	14	0.002	3187	3210	1
10	57.1	43.4	13.7	57.4	43.1	14.3	0.005	7965	8314	4
15	57.1	43.5	13.6	57.4	43.1	14.3	0.010	14538	15287	5
20	57.0	43.8	13.2	57.5	43.1	14.4	0.015	21465	23417	9
25	56.7	44.3	12.4	57.5	43.3	14.2	0.021	28462	32594	15
30	56.5	44.9	11.6	57.2	44	13.2	0.029	37158	42283	14
35	56.1	45.8	10.3	56.8	45	11.8	0.042	48164	55178	15
40	55.6	47.0	8.6	56.1	46.6	9.5	0.059	55857	61702	10
45	55.1	48.2	6.9	55.4	48.1	7.3	0.078	59189	62620	6
50	54.6	49.4	5.2	54.8	49.5	5.3	0.106	60761	61930	2
55	54.2	50.3	3.9	54.2	50.6	3.6	0.140	60309	55669	-8
60	53.9	51.1	2.8	53.8	51.4	2.4	0.192	59353	50874	-14
65	53.7	51.5	2.2	53.6	51.8	1.8	0.209	50848	41603	-18
70	53.6	51.8	1.8	53.5	52	1.5	0.228	45397	37831	-17
75	53.5	52.0	1.5	53.4	52.2	1.2	0.243	40297	32238	-20
80	53.4	52.1	1.3	53.3	52.4	0.9	0.267	38371	26565	-31
85	53.3	52.3	1	53.3	52.4	0.9	0.302	33385	30046	-10
90	53.3	52.5	0.8	53.3	52.5	0.8	0.232	20495	20495	0

Table C32: Maximum Dynamic Torque - 1,000 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	97264	60761	60
54	83703	60761	38
72	77290	60761	27
90	74043	60761	22
180	66051	60761	9
270	64336	60761	6
360	62620	60761	3

Table C33: Dynamic Torque Analysis – 36 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	57.2	43.3	13.9	57.5	43	14.5	0.002	3187	3324	4
10	57.1	43.4	13.7	58.2	42.3	15.9	0.005	7965	9244	16
15	57.1	43.5	13.6	58.5	42	16.5	0.010	14538	17638	21
20	57.0	43.7	13.3	59.4	41.2	18.2	0.015	21628	29596	37
25	56.9	44.2	12.7	60.5	40.4	20.1	0.021	29151	46137	58
30	56.7	44.7	12	60.3	41.2	19.1	0.029	38439	61183	59
35	56.4	45.6	10.8	60	42.6	17.4	0.042	50502	81365	61
40	56.0	46.7	9.3	58.5	45.2	13.3	0.059	60403	86383	43
45	55.6	48.0	7.6	57.3	47.4	9.9	0.078	65193	84923	30
50	55.2	49.3	5.9	56.2	49.3	6.9	0.106	68940	80625	17
55	54.8	50.3	4.5	55.3	50.8	4.5	0.140	69587	69587	0
60	54.6	51.2	3.4	54.7	51.7	3	0.192	72072	63593	-12
65	54.4	51.7	2.7	54.5	52.2	2.3	0.209	62404	53159	-15
70	54.3	52.1	2.2	54.3	52.5	1.8	0.228	55486	45397	-18
75	54.2	52.4	1.8	54.2	52.7	1.5	0.243	48357	40297	-17
80	54.1	52.6	1.5	54.1	52.9	1.2	0.267	44275	35420	-20
85	54.0	52.8	1.2	54	53	1	0.302	40062	33385	-17
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C34: Dynamic Torque Analysis – 54 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.4	43.1	14.3	0.002	3187	3278	3
10	57.1	43.4	13.7	57.9	42.6	15.3	0.005	7965	8896	12
15	57.1	43.5	13.6	58	42.5	15.5	0.010	14538	16569	14
20	57.0	43.7	13.3	58.5	42.1	16.4	0.015	21628	26669	23
25	56.9	44.2	12.7	59.2	41.7	17.5	0.021	29151	40169	38
30	56.7	44.7	12	58.9	42.5	16.4	0.029	38439	52534	37
35	56.4	45.6	10.8	58.8	43.5	15.3	0.042	50502	71545	42
40	56.0	46.7	9.3	57.7	45.6	12.1	0.059	60403	78589	30
45	55.6	48.0	7.6	56.9	47.5	9.4	0.078	65193	80634	24
50	55.2	49.3	5.9	56	49.3	6.7	0.106	68940	78288	14
55	54.8	50.3	4.5	55.2	50.8	4.4	0.140	69587	68040	-2
60	54.6	51.2	3.4	54.7	51.7	3	0.192	72072	63593	-12
65	54.4	51.7	2.7	54.4	52.2	2.2	0.209	62404	50848	-19
70	54.3	52.1	2.2	54.3	52.5	1.8	0.228	55486	45397	-18
75	54.2	52.4	1.8	54.2	52.7	1.5	0.243	48357	40297	-17
80	54.1	52.6	1.5	54.1	52.9	1.2	0.267	44275	35420	-20
85	54.0	52.8	1.2	54	53	1	0.302	40062	33385	-17
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C35: Dynamic Torque Analysis – 72 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.3	43.1	14.2	0.002	3187	3255	2
10	57.1	43.4	13.7	57.7	42.8	14.9	0.005	7965	8663	9
15	57.1	43.5	13.6	57.7	42.8	14.9	0.010	14538	15928	10
20	57.0	43.7	13.3	58.1	42.5	15.6	0.015	21628	25368	17
25	56.9	44.2	12.7	58.6	42.3	16.3	0.021	29151	37414	28
30	56.7	44.7	12	58.3	43	15.3	0.029	38439	49010	28
35	56.4	45.6	10.8	58.2	43.9	14.3	0.042	50502	66869	32
40	56.0	46.7	9.3	57.3	45.9	11.4	0.059	60403	74043	23
45	55.6	48.0	7.6	56.6	47.6	9	0.078	65193	77203	18
50	55.2	49.3	5.9	55.8	49.3	6.5	0.106	68940	75951	10
55	54.8	50.3	4.5	55.1	50.8	4.3	0.140	69587	66494	-4
60	54.6	51.2	3.4	54.6	51.7	2.9	0.192	72072	61473	-15
65	54.4	51.7	2.7	54.4	52.2	2.2	0.209	62404	50848	-19
70	54.3	52.1	2.2	54.3	52.5	1.8	0.228	55486	45397	-18
75	54.2	52.4	1.8	54.1	52.7	1.4	0.243	48357	37611	-22
80	54.1	52.6	1.5	54	52.9	1.1	0.267	44275	32468	-27
85	54.0	52.8	1.2	54	53	1	0.302	40062	33385	-17
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C36: Dynamic Torque Analysis – 90 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.3	43.2	14.1	0.002	3187	3233	1
10	57.1	43.4	13.7	57.6	42.9	14.7	0.005	7965	8547	7
15	57.1	43.5	13.6	57.6	42.9	14.7	0.010	14538	15714	8
20	57.0	43.7	13.3	57.9	42.7	15.2	0.015	21628	24718	14
25	56.9	44.2	12.7	58.2	42.6	15.6	0.021	29151	35808	23
30	56.7	44.7	12	58	43.3	14.7	0.029	38439	47088	23
35	56.4	45.6	10.8	57.9	44.2	13.7	0.042	50502	64063	27
40	56.0	46.7	9.3	57.1	46	11.1	0.059	60403	72094	19
45	55.6	48.0	7.6	56.4	47.7	8.7	0.078	65193	74629	14
50	55.2	49.3	5.9	55.7	49.4	6.3	0.106	68940	73614	7
55	54.8	50.3	4.5	55.1	50.8	4.3	0.140	69587	66494	-4
60	54.6	51.2	3.4	54.6	51.7	2.9	0.192	72072	61473	-15
65	54.4	51.7	2.7	54.4	52.1	2.3	0.209	62404	53159	-15
70	54.3	52.1	2.2	54.2	52.5	1.7	0.228	55486	42875	-23
75	54.2	52.4	1.8	54.1	52.7	1.4	0.243	48357	37611	-22
80	54.1	52.6	1.5	54	52.9	1.1	0.267	44275	32468	-27
85	54.0	52.8	1.2	54	53	1	0.302	40062	33385	-17
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C37: Dynamic Torque Analysis – 180 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.2	14	0.002	3187	3210	1
10	57.1	43.4	13.7	57.4	43.1	14.3	0.005	7965	8314	4
15	57.1	43.5	13.6	57.4	43.1	14.3	0.010	14538	15287	5
20	57.0	43.7	13.3	57.5	43.1	14.4	0.015	21628	23417	8
25	56.9	44.2	12.7	57.6	43.2	14.4	0.021	29151	33053	13
30	56.7	44.7	12	57.3	43.9	13.4	0.029	38439	42924	12
35	56.4	45.6	10.8	57.2	44.7	12.5	0.042	50502	58452	16
40	56.0	46.7	9.3	56.6	46.3	10.3	0.059	60403	66898	11
45	55.6	48.0	7.6	56	47.8	8.2	0.078	65193	70340	8
50	55.2	49.3	5.9	55.4	49.4	6	0.106	68940	70109	2
55	54.8	50.3	4.5	54.9	50.7	4.2	0.140	69587	64948	-7
60	54.6	51.2	3.4	54.5	51.6	2.9	0.192	72072	61473	-15
65	54.4	51.7	2.7	54.3	52.1	2.2	0.209	62404	50848	-19
70	54.3	52.1	2.2	54.2	52.4	1.8	0.228	55486	45397	-18
75	54.2	52.4	1.8	54.1	52.7	1.4	0.243	48357	37611	-22
80	54.1	52.6	1.5	54	52.9	1.1	0.267	44275	32468	-27
85	54.0	52.8	1.2	54	53	1	0.302	40062	33385	-17
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C38: Dynamic Torque Analysis – 270 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.3	13.9	0.002	3187	3187	0
10	57.1	43.4	13.7	57.3	43.2	14.1	0.005	7965	8198	3
15	57.1	43.5	13.6	57.3	43.2	14.1	0.010	14538	15073	4
20	57.0	43.7	13.3	57.4	43.2	14.2	0.015	21628	23092	7
25	56.9	44.2	12.7	57.4	43.4	14	0.021	29151	32135	10
30	56.7	44.7	12	57.2	44	13.2	0.029	38439	42283	10
35	56.4	45.6	10.8	57	44.9	12.1	0.042	50502	56581	12
40	56.0	46.7	9.3	56.4	46.4	10	0.059	60403	64950	8
45	55.6	48.0	7.6	55.9	47.9	8	0.078	65193	68625	5
50	55.2	49.3	5.9	55.4	49.4	6	0.106	68940	70109	2
55	54.8	50.3	4.5	54.9	50.7	4.2	0.140	69587	64948	-7
60	54.6	51.2	3.4	54.5	51.6	2.9	0.192	72072	61473	-15
65	54.4	51.7	2.7	54.3	52.1	2.2	0.209	62404	50848	-19
70	54.3	52.1	2.2	54.2	52.4	1.8	0.228	55486	45397	-18
75	54.2	52.4	1.8	54.1	52.7	1.4	0.243	48357	37611	-22
80	54.1	52.6	1.5	54	52.9	1.1	0.267	44275	32468	-27
85	54.0	52.8	1.2	54	52.9	1.1	0.302	40062	36723	-8
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C39: Dynamic Torque Analysis – 360 second closure time - 500 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.3	13.9	0.002	3187	3187	0
10	57.1	43.4	13.7	57.3	43.2	14.1	0.005	7965	8198	3
15	57.1	43.5	13.6	57.3	43.2	14.1	0.010	14538	15073	4
20	57.0	43.7	13.3	57.3	43.3	14	0.015	21628	22766	5
25	56.9	44.2	12.7	57.3	43.5	13.8	0.021	29151	31676	9
30	56.7	44.7	12	57.1	44.1	13	0.029	38439	41643	8
35	56.4	45.6	10.8	56.8	45	11.8	0.042	50502	55178	9
40	56.0	46.7	9.3	56.3	46.5	9.8	0.059	60403	63651	5
45	55.6	48.0	7.6	55.8	47.9	7.9	0.078	65193	67767	4
50	55.2	49.3	5.9	55.3	49.4	5.9	0.106	68940	68940	0
55	54.8	50.3	4.5	54.8	50.7	4.1	0.140	69587	63401	-9
60	54.6	51.2	3.4	54.5	51.6	2.9	0.192	72072	61473	-15
65	54.4	51.7	2.7	54.3	52.1	2.2	0.209	62404	50848	-19
70	54.3	52.1	2.2	54.2	52.4	1.8	0.228	55486	45397	-18
75	54.2	52.4	1.8	54.1	52.7	1.4	0.243	48357	37611	-22
80	54.1	52.6	1.5	54	52.9	1.1	0.267	44275	32468	-27
85	54.0	52.8	1.2	54	52.9	1.1	0.302	40062	36723	-8
90	54.0	53.0	1	54	53	1	0.232	25619	25619	0

Table C40: Maximum Dynamic Torque - 500 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	86383	72072	20
54	80634	72072	12
72	77203	72072	7
90	74629	72072	4
180	70340	72072	-2
270	70109	72072	-3
360	68940	72072	-4

Table C41: Dynamic Torque Analysis – 36 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.3	43.2	14.1	0.002	3187	3233	1
10	57.1	43.4	13.7	57.6	42.8	14.8	0.005	7965	8605	8
15	57.1	43.5	13.6	57.7	42.8	14.9	0.010	14538	15928	10
20	57.1	44.0	13.1	58.1	42.5	15.6	0.015	21303	25368	19
25	56.9	44.1	12.8	58.5	42.3	16.2	0.021	29381	37185	27
30	56.8	44.6	12.2	58.4	43	15.4	0.029	39080	49330	26
35	56.6	45.5	11.1	58.4	43.8	14.6	0.042	51905	68272	32
40	56.3	46.6	9.7	57.6	45.7	11.9	0.059	63001	77290	23
45	55.9	47.8	8.1	57	47.5	9.5	0.078	69482	81492	17
50	55.6	49.2	6.4	56.3	49.3	7	0.106	74783	81794	9
55	55.3	50.4	4.9	55.6	50.9	4.7	0.140	75772	72680	-4
60	55.0	51.3	3.7	55.1	51.9	3.2	0.192	78431	67832	-14
65	54.9	51.9	3	54.9	52.4	2.5	0.209	69338	57781	-17
70	54.7	52.3	2.4	54.7	52.8	1.9	0.228	60530	47919	-21
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C42: Dynamic Torque Analysis – 54 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.3	43.2	14.1	0.002	3187	3233	1
10	57.1	43.4	13.7	57.5	43	14.5	0.005	7965	8430	6
15	57.1	43.5	13.6	57.5	43	14.5	0.010	14538	15500	7
20	57.1	44.0	13.1	57.7	42.9	14.8	0.015	21303	24067	13
25	56.9	44.1	12.8	58	42.8	15.2	0.021	29381	34889	19
30	56.8	44.6	12.2	57.8	43.5	14.3	0.029	39080	45807	17
35	56.6	45.5	11.1	57.8	44.3	13.5	0.042	51905	63128	22
40	56.3	46.6	9.7	57.2	46	11.2	0.059	63001	72744	15
45	55.9	47.8	8.1	56.7	47.6	9.1	0.078	69482	78061	12
50	55.6	49.2	6.4	56.1	49.3	6.8	0.106	74783	79457	6
55	55.3	50.4	4.9	55.5	50.8	4.7	0.140	75772	72680	-4
60	55.0	51.3	3.7	55.1	51.8	3.3	0.192	78431	69952	-11
65	54.9	51.9	3	54.8	52.4	2.4	0.209	69338	55470	-20
70	54.7	52.3	2.4	54.7	52.7	2	0.228	60530	50442	-17
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C43: Dynamic Torque Analysis – 72 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.2	14	0.002	3187	3210	1
10	57.1	43.4	13.7	57.4	43.1	14.3	0.005	7965	8314	4
15	57.1	43.5	13.6	57.4	43.1	14.3	0.010	14538	15287	5
20	57.1	44.0	13.1	57.6	43	14.6	0.015	21303	23742	11
25	56.9	44.1	12.8	57.7	43.1	14.6	0.021	29381	33512	14
30	56.8	44.6	12.2	57.5	43.7	13.8	0.029	39080	44205	13
35	56.6	45.5	11.1	57.5	44.5	13	0.042	51905	60790	17
40	56.3	46.6	9.7	57	46.1	10.9	0.059	63001	70795	12
45	55.9	47.8	8.1	56.5	47.7	8.8	0.078	69482	75487	9
50	55.6	49.2	6.4	55.9	49.3	6.6	0.106	74783	77120	3
55	55.3	50.4	4.9	55.4	50.8	4.6	0.140	75772	71133	-6
60	55.0	51.3	3.7	55	51.8	3.2	0.192	78431	67832	-14
65	54.9	51.9	3	54.8	52.4	2.4	0.209	69338	55470	-20
70	54.7	52.3	2.4	54.7	52.7	2	0.228	60530	50442	-17
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C44: Dynamic Torque Analysis – 90 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Upstream Pressure (psi)**	**Downstream Pressure (psi)**	**Pressure Difference (psi)**	**Ct**	**S.S. Torque (in-lbs)**	**Transient Torque (in-lbs)**	**% Difference**
5	57.2	43.3	13.9	57.2	43.2	14	0.002	3187	3210	1
10	57.1	43.4	13.7	57.4	43.1	14.3	0.005	7965	8314	4
15	57.1	43.5	13.6	57.4	43.1	14.3	0.010	14538	15287	5
20	57.1	44.0	13.1	57.5	43.1	14.4	0.015	21303	23417	10
25	56.9	44.1	12.8	57.6	43.2	14.4	0.021	29381	33053	13
30	56.8	44.6	12.2	57.4	43.8	13.6	0.029	39080	43565	11
35	56.6	45.5	11.1	57.3	44.6	12.7	0.042	51905	59387	14
40	56.3	46.6	9.7	56.8	46.2	10.6	0.059	63001	68847	9
45	55.9	47.8	8.1	56.4	47.7	8.7	0.078	69482	74629	7
50	55.6	49.2	6.4	55.9	49.3	6.6	0.106	74783	77120	3
55	55.3	50.4	4.9	55.4	50.8	4.6	0.140	75772	71133	-6
60	55.0	51.3	3.7	55	51.8	3.2	0.192	78431	67832	-14
65	54.9	51.9	3	54.8	52.3	2.5	0.209	69338	57781	-17
70	54.7	52.3	2.4	54.7	52.7	2	0.228	60530	50442	-17
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C45: Dynamic Torque Analysis – 180 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.3	13.9	0.002	3187	3187	0
10	57.1	43.4	13.7	57.3	43.2	14.1	0.005	7965	8198	3
15	57.1	43.5	13.6	57.3	43.2	14.1	0.010	14538	15073	4
20	57.1	44.0	13.1	57.3	43.3	14	0.015	21303	22766	7
25	56.9	44.1	12.8	57.3	43.5	13.8	0.021	29381	31676	8
30	56.8	44.6	12.2	57.1	44	13.1	0.029	39080	41963	7
35	56.6	45.5	11.1	57	44.9	12.1	0.042	51905	56581	9
40	56.3	46.6	9.7	56.6	46.3	10.3	0.059	63001	66898	6
45	55.9	47.8	8.1	56.2	47.8	8.4	0.078	69482	72056	4
50	55.6	49.2	6.4	55.7	49.3	6.4	0.106	74783	74783	0
55	55.3	50.4	4.9	55.3	50.8	4.5	0.140	75772	69587	-8
60	55.0	51.3	3.7	55	51.8	3.2	0.192	78431	67832	-14
65	54.9	51.9	3	54.8	52.3	2.5	0.209	69338	57781	-17
70	54.7	52.3	2.4	54.7	52.7	2	0.228	60530	50442	-17
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C46: Dynamic Torque Analysis – 270 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.3	13.9	0.002	3187	3187	0
10	57.1	43.4	13.7	57.2	43.2	14	0.005	7965	8140	2
15	57.1	43.5	13.6	57.2	43.3	13.9	0.010	14538	14859	2
20	57.1	44.0	13.1	57.2	43.3	13.9	0.015	21303	22604	6
25	56.9	44.1	12.8	57.2	43.5	13.7	0.021	29381	31446	7
30	56.8	44.6	12.2	57.1	44.1	13	0.029	39080	41643	7
35	56.6	45.5	11.1	56.9	45	11.9	0.042	51905	55646	7
40	56.3	46.6	9.7	56.5	46.4	10.1	0.059	63001	65599	4
45	55.9	47.8	8.1	56.1	47.8	8.3	0.078	69482	71198	2
50	55.6	49.2	6.4	55.7	49.3	6.4	0.106	74783	74783	0
55	55.3	50.4	4.9	55.3	50.8	4.5	0.140	75772	69587	-8
60	55.0	51.3	3.7	54.9	51.8	3.1	0.192	78431	65712	-16
65	54.9	51.9	3	54.8	52.3	2.5	0.209	69338	57781	-17
70	54.7	52.3	2.4	54.7	52.7	2	0.228	60530	50442	-17
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C47: Dynamic Torque Analysis – 360 second closure time - 250 ft Pipeline

	Steady State Results			Transient Results			Dynamic Torque			
Valve Open (degrees)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Upstream Pressure (psi)	Downstream Pressure (psi)	Pressure Difference (psi)	Ct	S.S. Torque (in-lbs)	Transient Torque (in-lbs)	% Difference
5	57.2	43.3	13.9	57.2	43.3	13.9	0.002	3187	3187	0
10	57.1	43.4	13.7	57.2	43.3	13.9	0.005	7965	8082	1
15	57.1	43.5	13.6	57.2	43.3	13.9	0.010	14538	14859	2
20	57.1	44.0	13.1	57.2	43.4	13.8	0.015	21303	22441	5
25	56.9	44.1	12.8	57.2	43.6	13.6	0.021	29381	31217	6
30	56.8	44.6	12.2	57	44.2	12.8	0.029	39080	41002	5
35	56.6	45.5	11.1	56.8	45	11.8	0.042	51905	55178	6
40	56.3	46.6	9.7	56.4	46.4	10	0.059	63001	64950	3
45	55.9	47.8	8.1	56	47.8	8.2	0.078	69482	70340	1
50	55.6	49.2	6.4	55.6	49.3	6.3	0.106	74783	73614	-2
55	55.3	50.4	4.9	55.2	50.8	4.4	0.140	75772	68040	-10
60	55.0	51.3	3.7	54.9	51.7	3.2	0.192	78431	67832	-14
65	54.9	51.9	3	54.8	52.3	2.5	0.209	69338	57781	-17
70	54.7	52.3	2.4	54.7	52.7	2	0.228	60530	50442	-17
75	54.7	52.6	2.1	54.6	53	1.6	0.243	56416	42984	-24
80	54.6	52.9	1.7	54.5	53.2	1.3	0.267	50178	38371	-24
85	54.5	53.1	1.4	54.5	53.3	1.2	0.302	46739	40062	-14
90	54.5	53.3	1.2	54.5	53.3	1.2	0.232	30742	30742	0

Table C48: Maximum Dynamic Torque - 250 ft Pipeline

Valve Closure Time (seconds)	Max. Transient Dynamic Torque (in-lbs)	Max. Steady State Dynamic Torque (in-lbs)	% Difference
36	81794	78431	4
54	79457	78431	1
72	77120	78431	-2
90	77120	78431	-2
180	74783	78431	-5
270	74783	78431	-5
360	73614	78431	-6